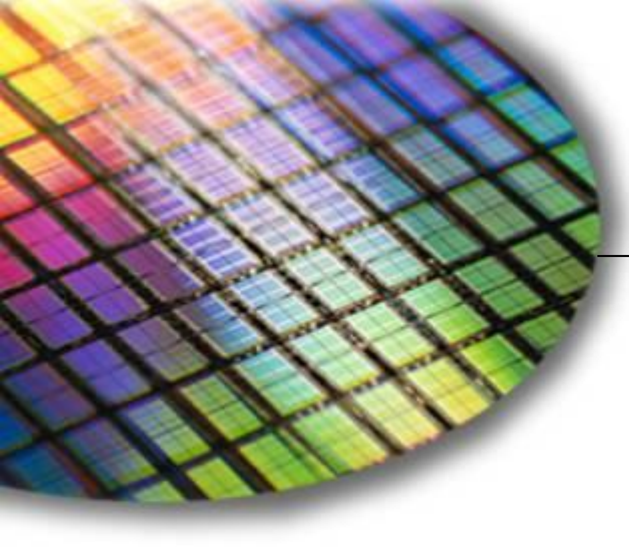


The World Leader in High Performance Signal Processing Solutions

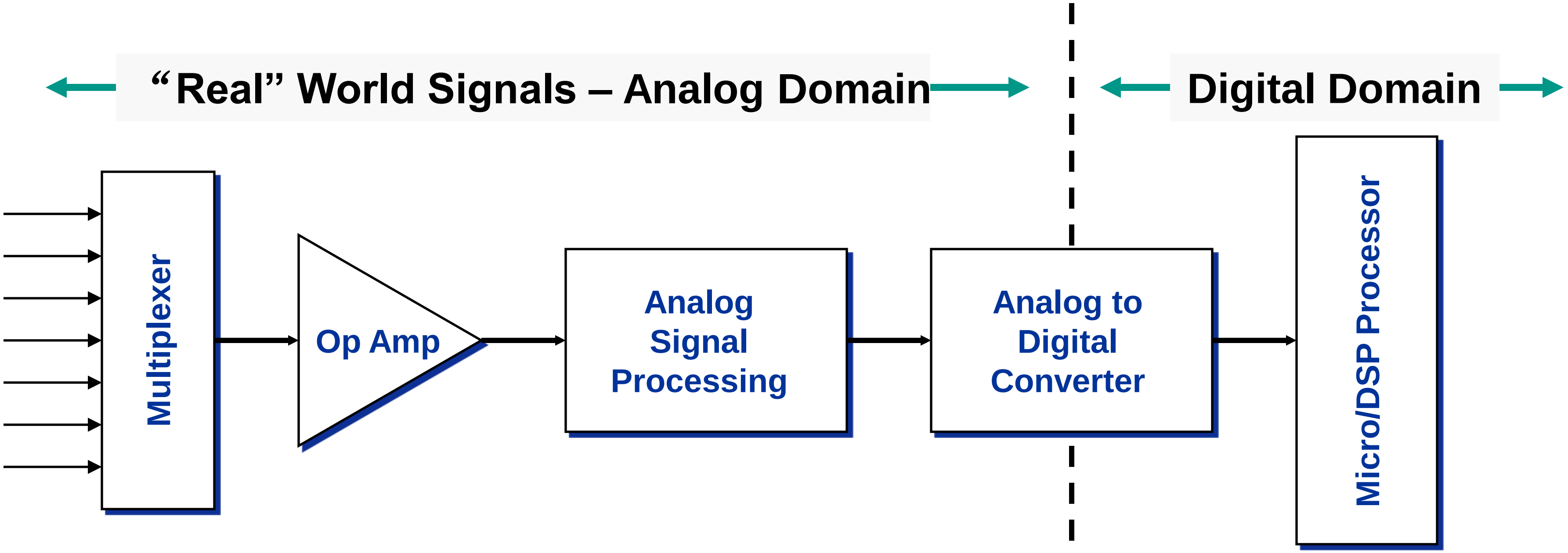
Amplifiers

Op Amps & Specialty Amps
Applications & Specifications

Agenda: Operational Amplifiers

- Applications for op-amps
- Architectures
- Choosing an op amp for your application
  - Specifications for DC performance
  - Specifications for AC performance
  - Specifications that affect DC & AC performance
- Other types of amplifiers
  - Instrumentation Amps
  - Log Amps
  - Variable Gain Amps
  - Difference Amps
  - Differential Amps

Amplifiers Are Used For…



“Real” World Signals – Analog Domain

Digital Domain

Multiplexer

Op Amp

Analog Signal Processing

Analog to Digital Converter

Micro/DSP Processor

- Amplification of AC and/or DC Signals
- Buffering (High Input & Low Output Impedance)
  - Amplifiers often used to drive ADCs
- Driving Signals
- Gain & Level Shifting
- Filters

ALSO

- Current-to-Voltage or Voltage-to-current Conversion
- Mathematical Operations:
  - Summing or Subtracting 2 or More Signals
  - Integration or Differentiation

Basic Architectures

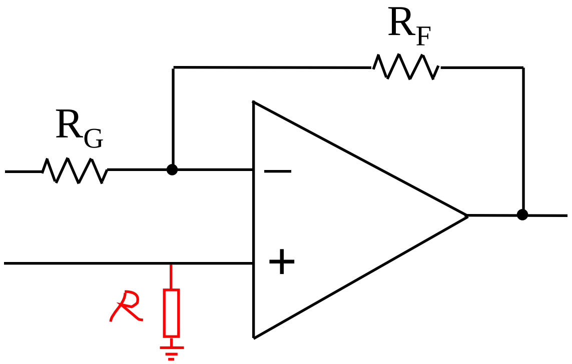
- Voltage Feedback
  - Text Book Op Amp

- Current Feedback
  - Also called Transimpedance Amps
  - Typically Higher Speeds than Voltage Feedback

- Both Types of Architectures Respond to Input Signals by Forcing the + and - Inputs To the Same Voltage

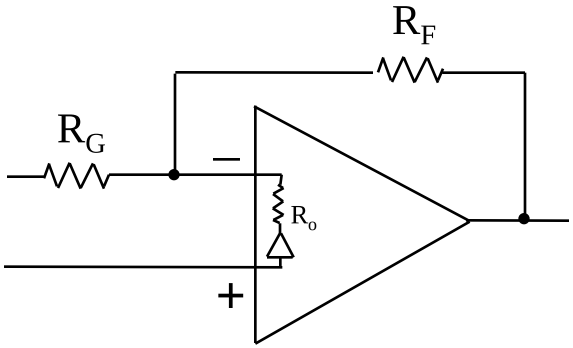
Voltage Feedback Vs Current Feedback

Voltage Feedback



- Responds to an Error Voltage between the Inputs
- Balanced, High Impedance on + and - Inputs
- Constant Gain Bandwidth Product
  - Can reduce Johnson noise with low R values
  - G = 2, BW = 100 MHz
    G=20, BW = 10 MHz

Current Feedback

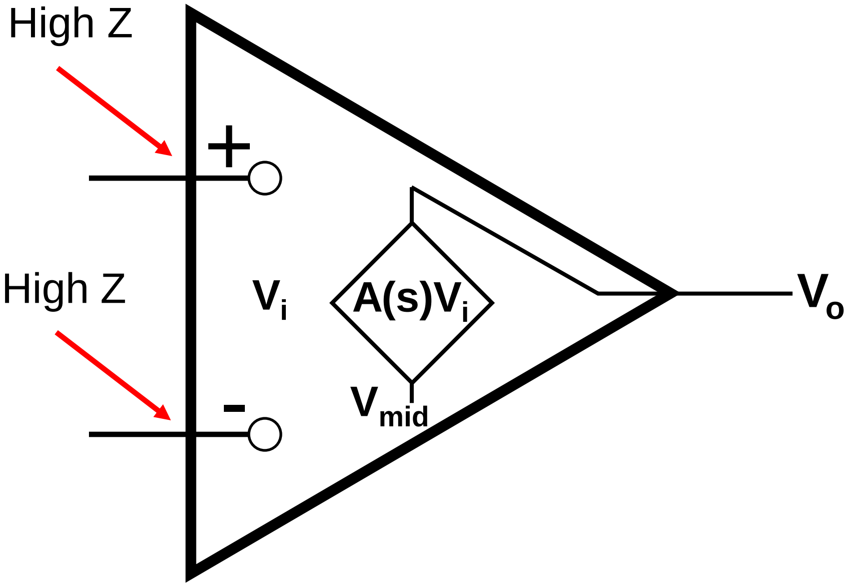


- Responds to a Current Error on an Input
- High + Input and Low - Input Impedances
- Bandwidth Set by Feedback Resistor
  - Increasing R_F reduces BW
  - Decreasing R_F reduces stability

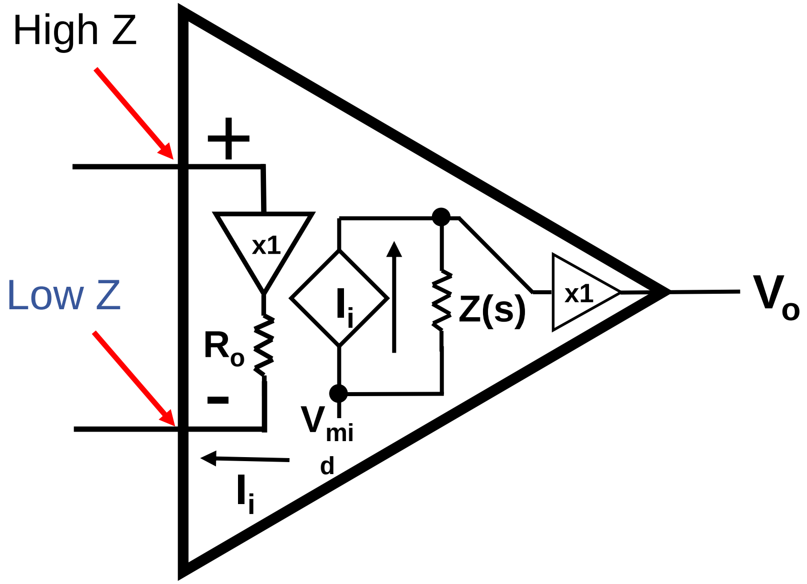
High-Level Block Diagrams

Voltage Feedback and Current Feedback Comparison

Voltage Feedback



Current Feedback

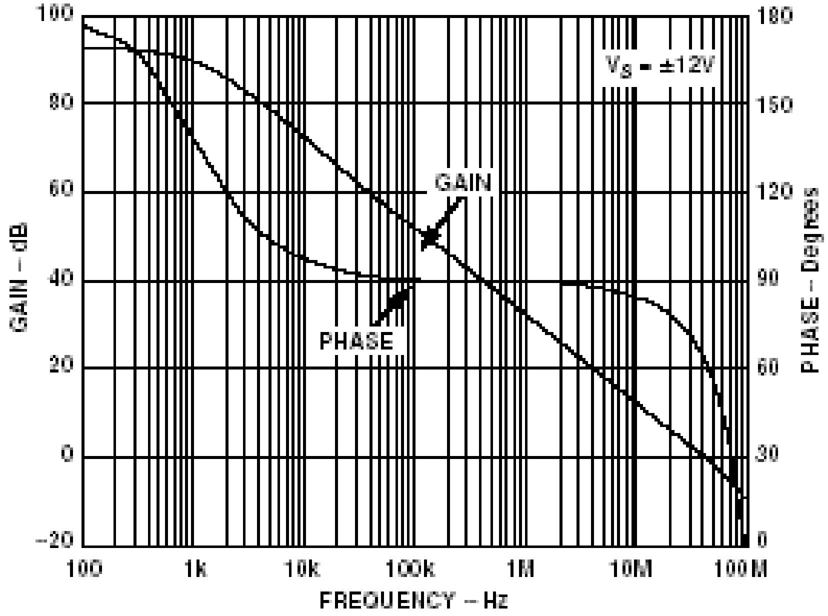


- $V_o = A(s)*(V_i)$
- $A(s) = A_o*\omega_p/(s + \omega_p)$
- Large DC Gain, A_o
- Negative feedback drives input voltage V_i to nearly zero

- $V_o = Z(s)*(I_i)$
- $Z(s) = Z_o*\omega_p/(s + \omega_p)$
- Large DC Transimpedance, Z_o
- Negative feedback drives input current I_i to nearly zero

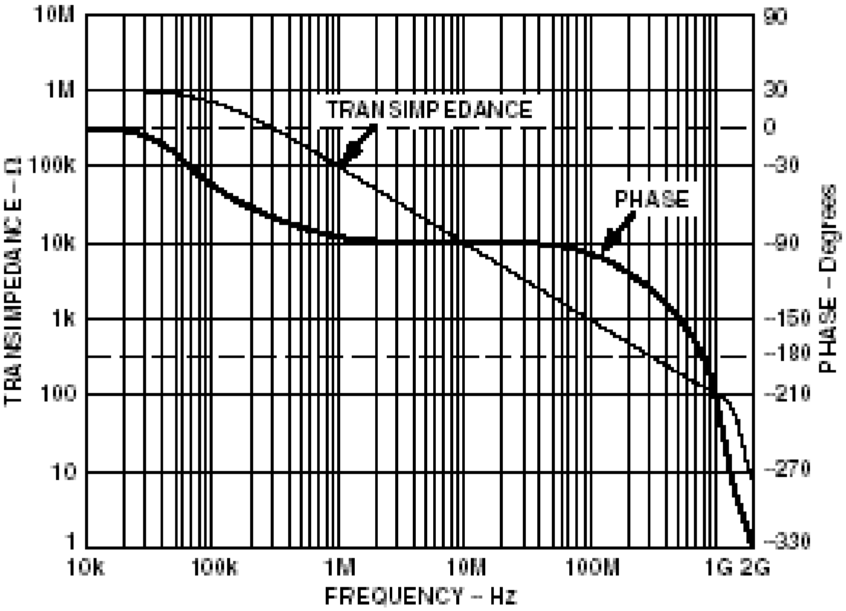
Voltage Feedback and Current Feedback Open-Loop Characteristics

Voltage Feedback



TPC 12. *Open-Loop Response*

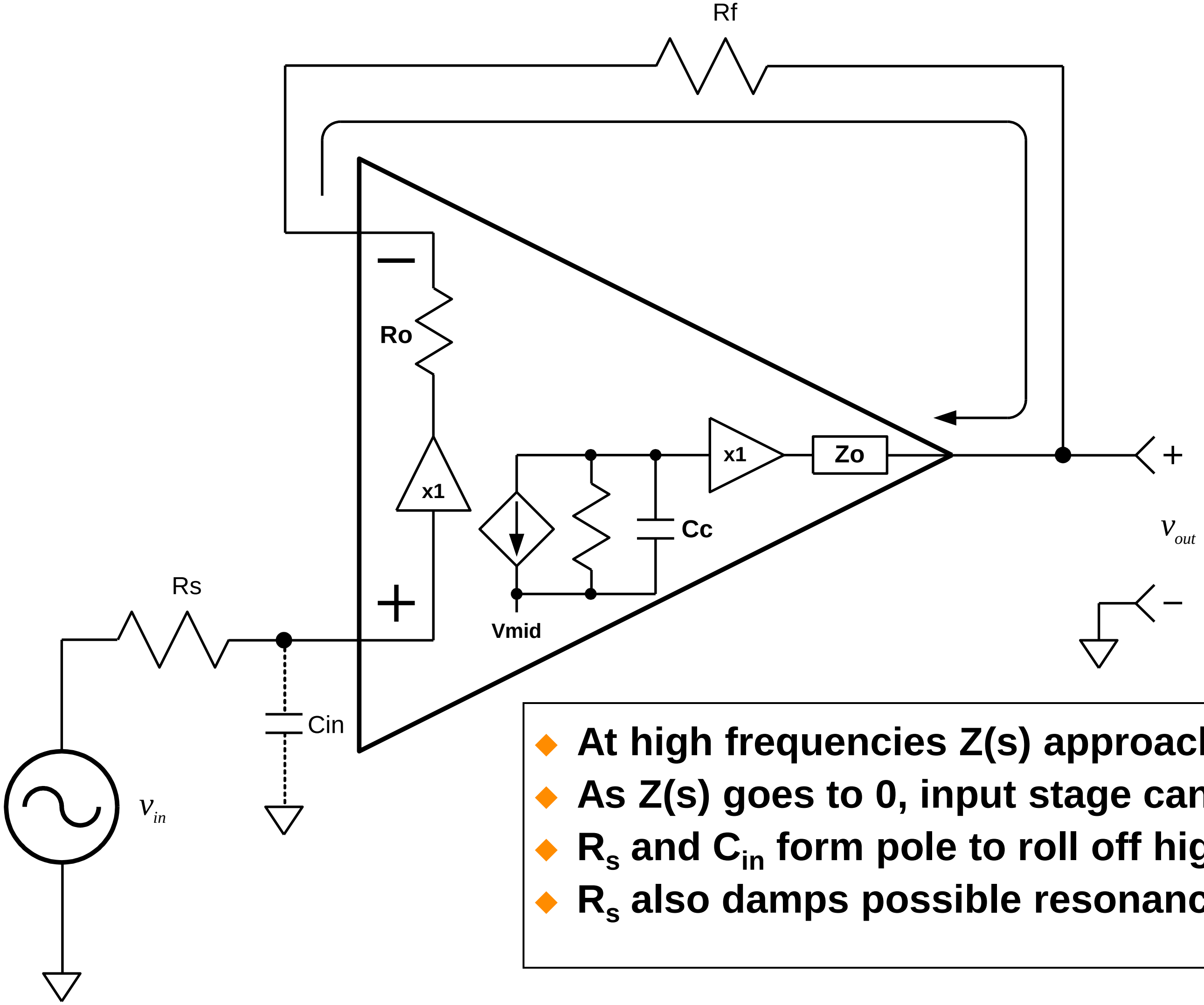
Current Feedback



TPC 10. *Transimpedance and Phase vs. Frequency*

Series Resistance on (+) Input

Some CFB Amplifiers Require a Resistor In Series With the (+) Input.

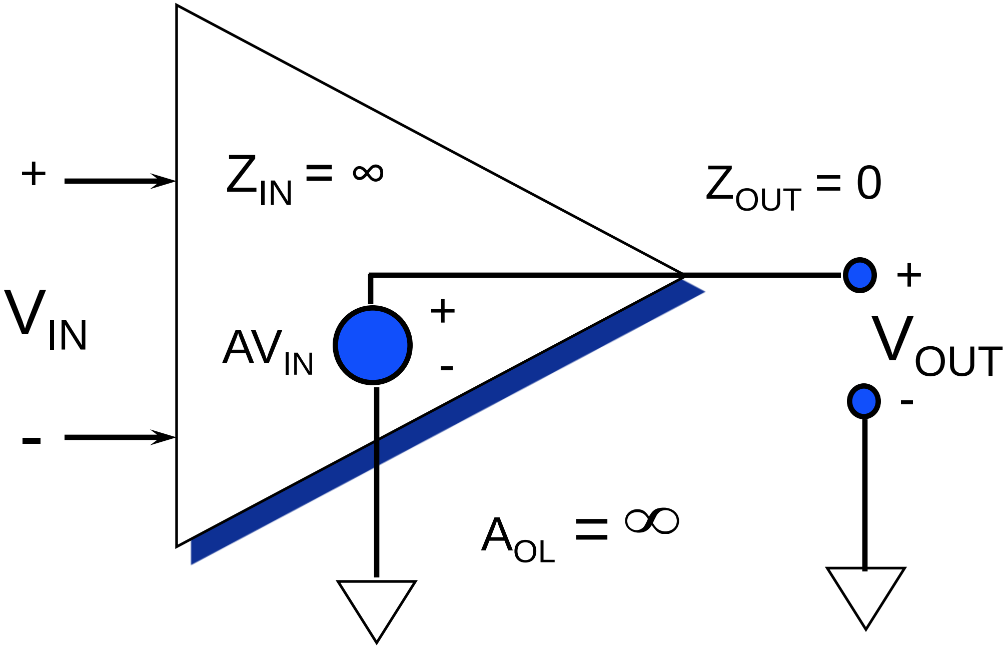


- At high frequencies Z(s) approaches 0.
- As Z(s) goes to 0, input stage can drive output stage.
- R_s and C_{in} form pole to roll off high frequencies.
- R_s also damps possible resonances in input stage.

Choosing the Right Op Amp

Ideal Op Amp Characteristics:

- Infinite input impedance
- Zero output impedance
- Infinite bandwidth
- Infinite open loop gain
- No DC Errors

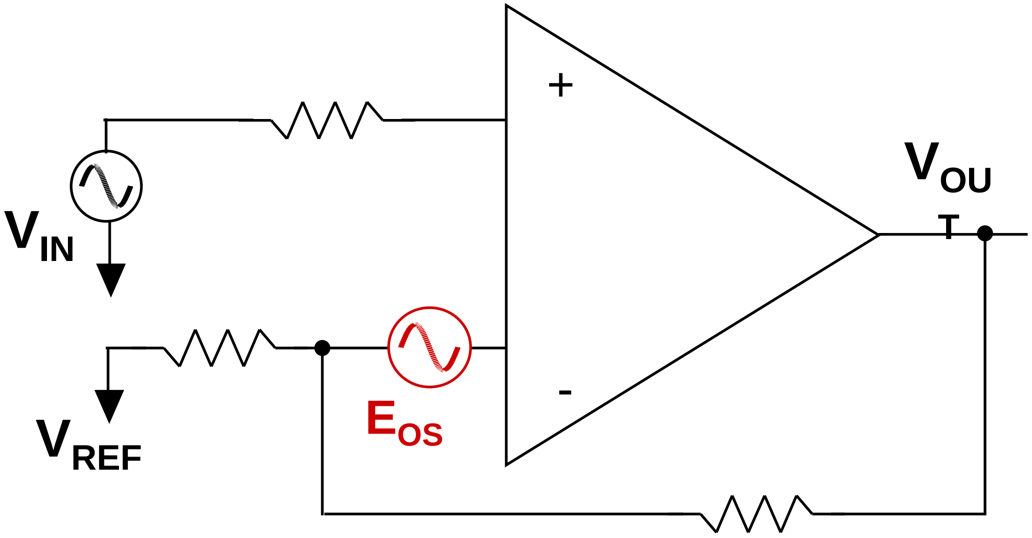


Sources of Error in Op Amps

- DC or Low Frequency Performance affected by:
  - Offset Voltage
  - Input Bias Current
  - Thermal Drift
  - 1/f noise
- AC Performance affected by:
  - BW (Bandwidth)
  - Slew Rate
  - Gain Error
  - Settling Time
  - Noise
  - Distortion
- Additional Specifications
  - CMRR (Common Mode Rejection Ratio)
  - PSRR (Power Supply Rejection Ratio)
  - Input Common Mode Range
  - Low Power and Rail to Rail Operation

Op Amp Specifications
Offset Voltage

- Adds a small voltage to the input
- $V_{OUT} = \text{Gain}(V_{IN} + E_{OS})$
- High Gain or High E_{OS} increases effect on output.

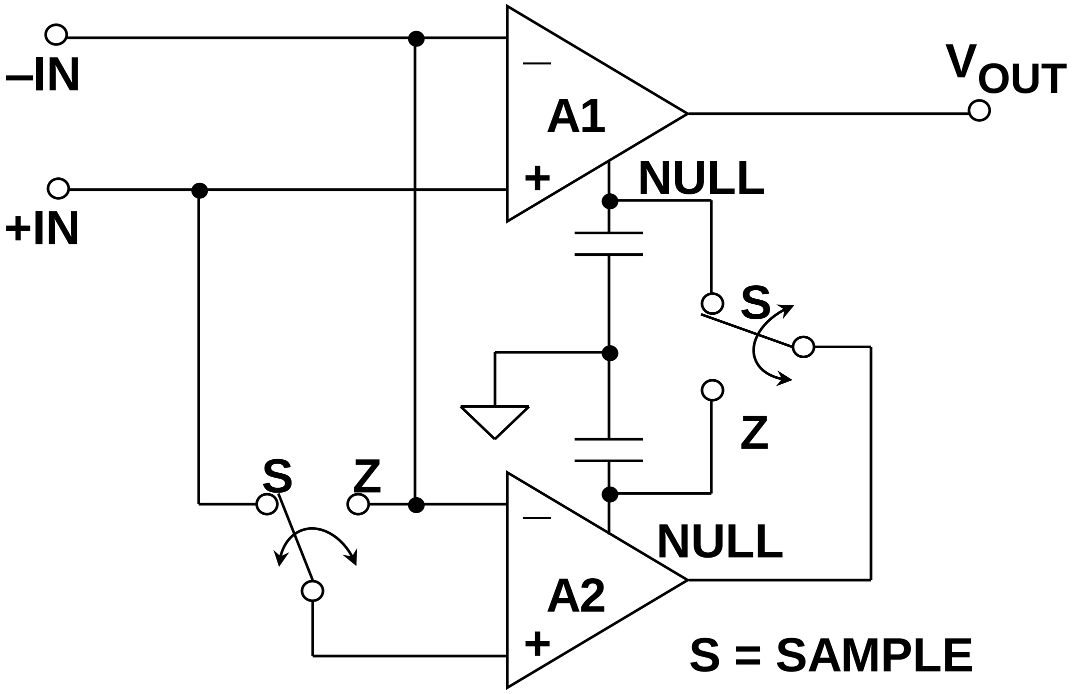


- Offset Voltage due to differences in input transistors
- E_{OS} can be positive or negative
- How to measure it:
  - Configure amplifier for very high gain (G>100)
  - Ground both inputs
  - Measure output voltage
  - $E_{OS} = V_{OUT}/\text{Gain}$

Op Amp Specifications

Offset Voltage: Reducing the Error

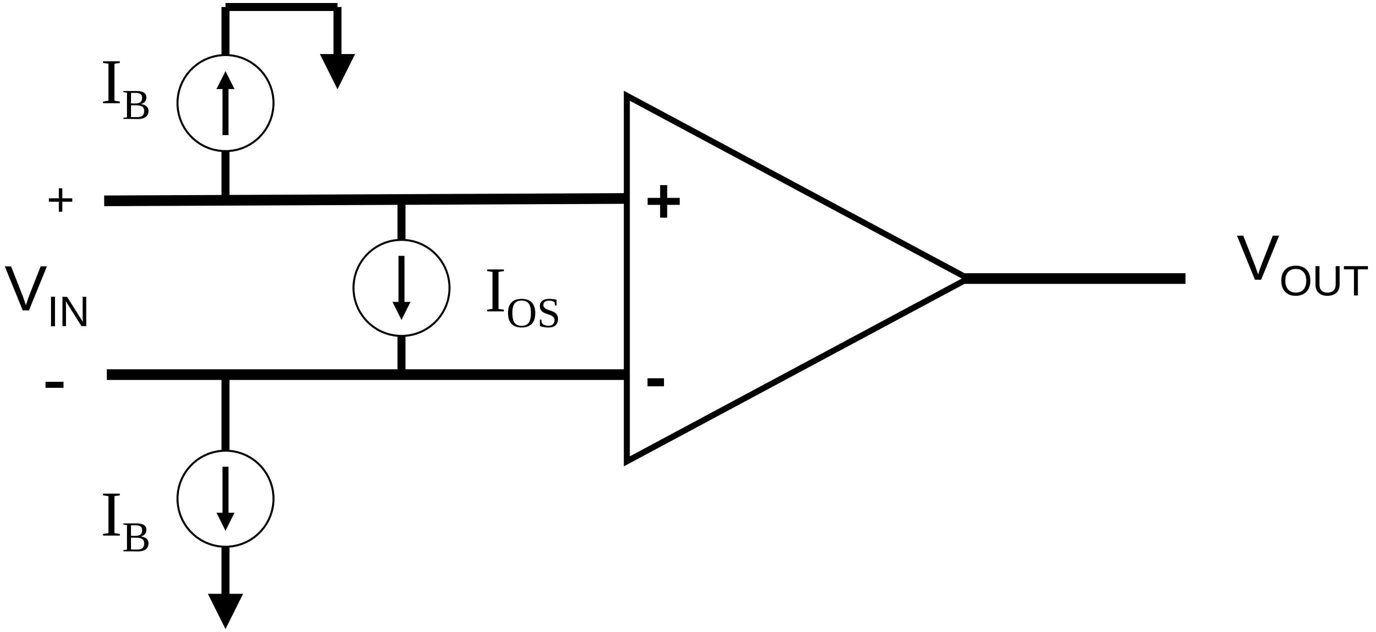
- System calibration can compensate for initial offset voltage
- Offset voltage changes with temperature and time
- Auto-Zero Op Amps:
  - Second op amp (A2) corrects offset error of first op amp (A1)
  - Eliminates change over time and temperature!
  - Also reduces 1/f (low frequency) noise
  - Used in the same way as other op amps
  - See AD8552 data sheet for complete theory



S = SAMPLE
Z = AUTO-ZERO

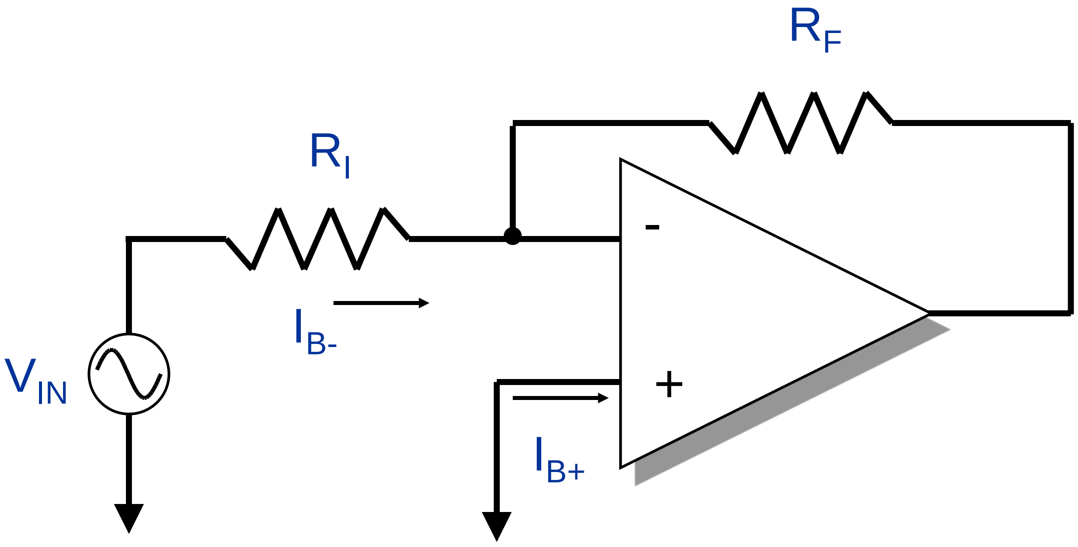
Op Amp Specifications

Input Bias Current and Offset Current



- Offset error is a function of I_B, I_{OS}, and the resistors connected around the amplifier
- I_B is the main source of error
  - I_B is usually > 10 x I_{OS}
- Low I_B op amps can use large resistors without causing dramatic errors

The Effects of Input Bias Current

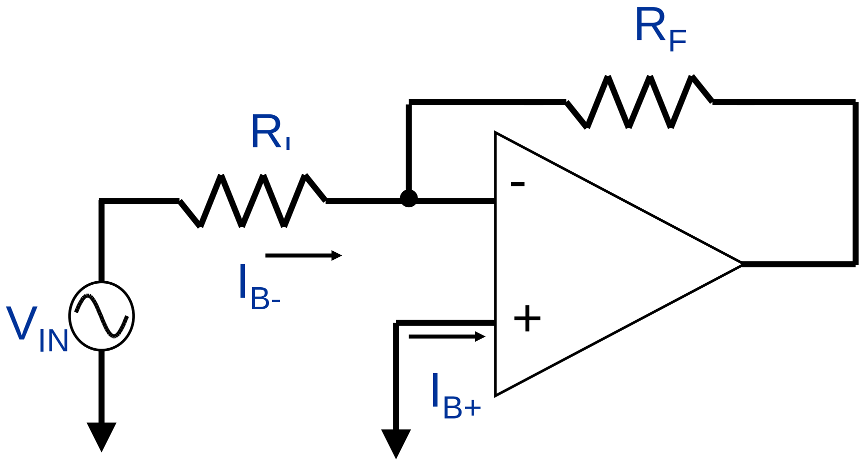


$$V_{OUT} = -\left(V_{IN}/R_I \pm I_{B-}\right) \times R_F$$

The bias current will introduce an error term depending on the values of the bias current and the source resistance

Op Amp Specifications
Bias Current: Reducing the Error

- **CMOS and JFET input stages have the lowest I_B**
  - Down to 10pA or less
  - For example: AD8605, AD8033
  - I_B of FET input op amps varies with temperature
- **Input bias canceled op amps also have very low I_B**
  - Most are < 10nA
  - For example: OP27



$$V_{OUT} = -\left(V_{IN}/R_I \pm I_{B-}\right) \times R_F$$

The bias current will introduce an error term depending on the values of the bias current and the source resistance

Op Amp Specifications

Temperature Drift

- How a parameter changes with Temperature
- Common drift specifications are V_{OS}, Gain, I_B
- Every product has different drift behavior
  - Auto-zero and Gain Programmable Amplifiers typically have the lowest drift
- Example of Temperature Drift graphs:

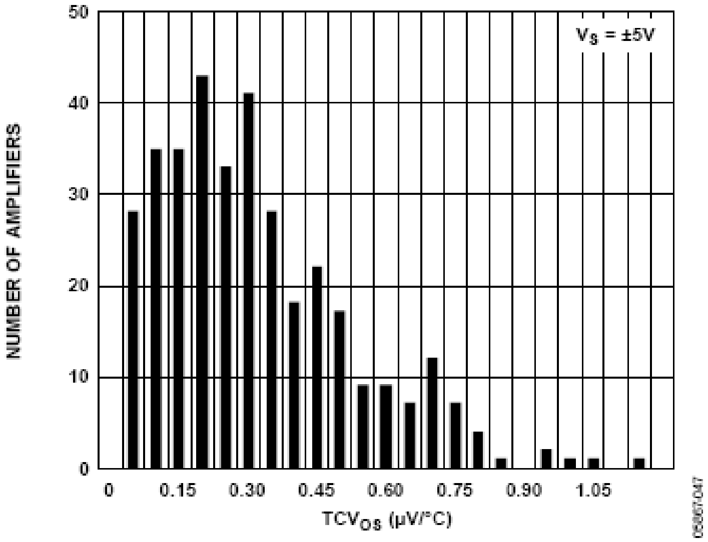


Figure 4. Number of Amplifiers vs. TCV$_{OS}$

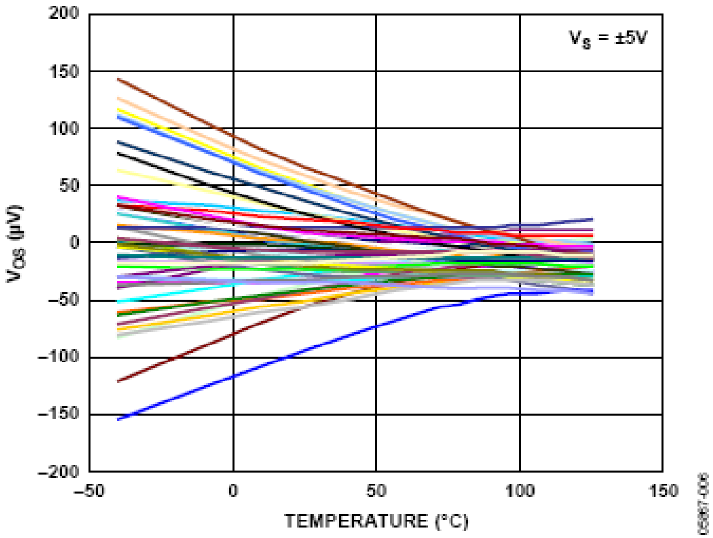


Figure 7. Offset Voltage vs. Temperature

Temperature Drift: Converting to resolution or % error

- **Example application:**
  - **Measuring 0-100 mV output from a sensor**
  - **Operating from -10° C to 50° C**
  - **Offset voltage change is 1.5µV/° C**
  - **Initial calibration performed at 25° C**
- **Calculate difference in offset voltage due to temperature**
  - **50° C - 25° C = 25° C**
  - **25° C – (-10° C) = 35° C (The larger temperature change)**
  - **(1.5µV/° C)*(35° C) = 52.5µV**
- **Convert the difference in offset voltage to resolution**
  - **Full scale signal is 100mV**
  - **52.5µV / 100mV = 0.000526 (or 0.0526%, or 526 ppm)**
  - **How many bits is that?**

    $2^X = 1/(0.000526)$

    $2^X = 1901$

    $\text{Log}_2\,(1901) = x$ If your calculator does not have a log base 2 function …

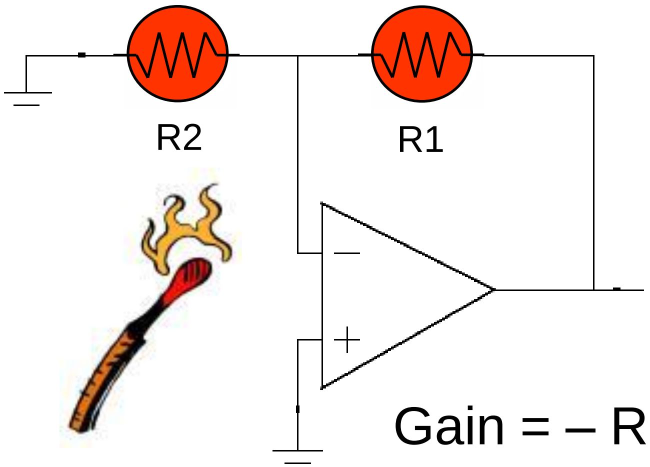
    $\text{Log}_{10}(1901)/\text{Log}_{10}(2) = x$

    x = 10.89, or almost 11 bits of resolution are possible with this amount of temperature drift

Op Amp Specifications

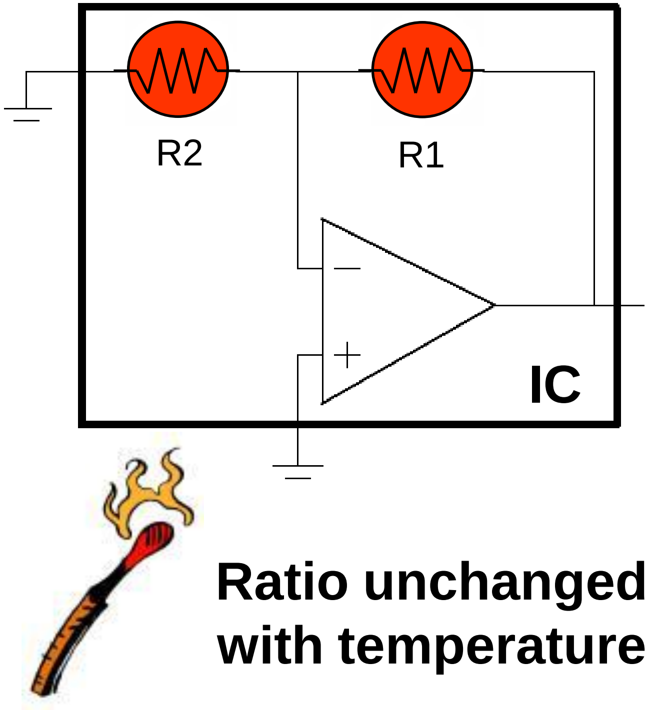
Temperature Drift: Reducing the Error

- Auto-zero and Gain Programmable Amplifiers typically have the lowest drift
- Integrating gain resistors reduces temperature drift errors



Gain = – R1 / R2

Ratio Changed with Temperature!



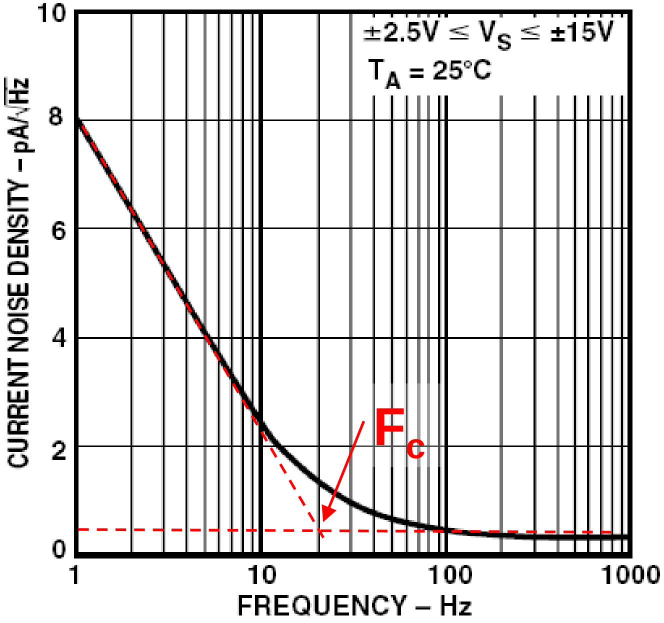
Ratio unchanged with temperature

No Drift!

Op Amp Specifications

Low Frequency Noise

- At low frequencies voltage & current noise density rise.
- 1/f noise has a corner frequency: F_C
- Voltage noise frequently specified as peak value for 0.1 – 10Hz
- To calculate RMS noise in 1/f region from F_L to F_H (where K = noise at 1 Hz): $K \cdot \sqrt{\ln(F_H/F_L)}$
- Multiply RMS by 6.6 to estimate peak-to-peak value

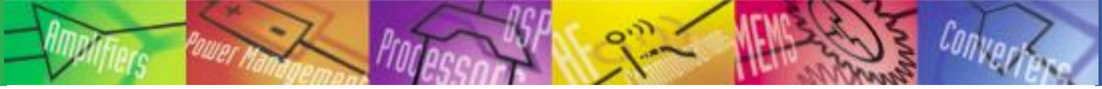


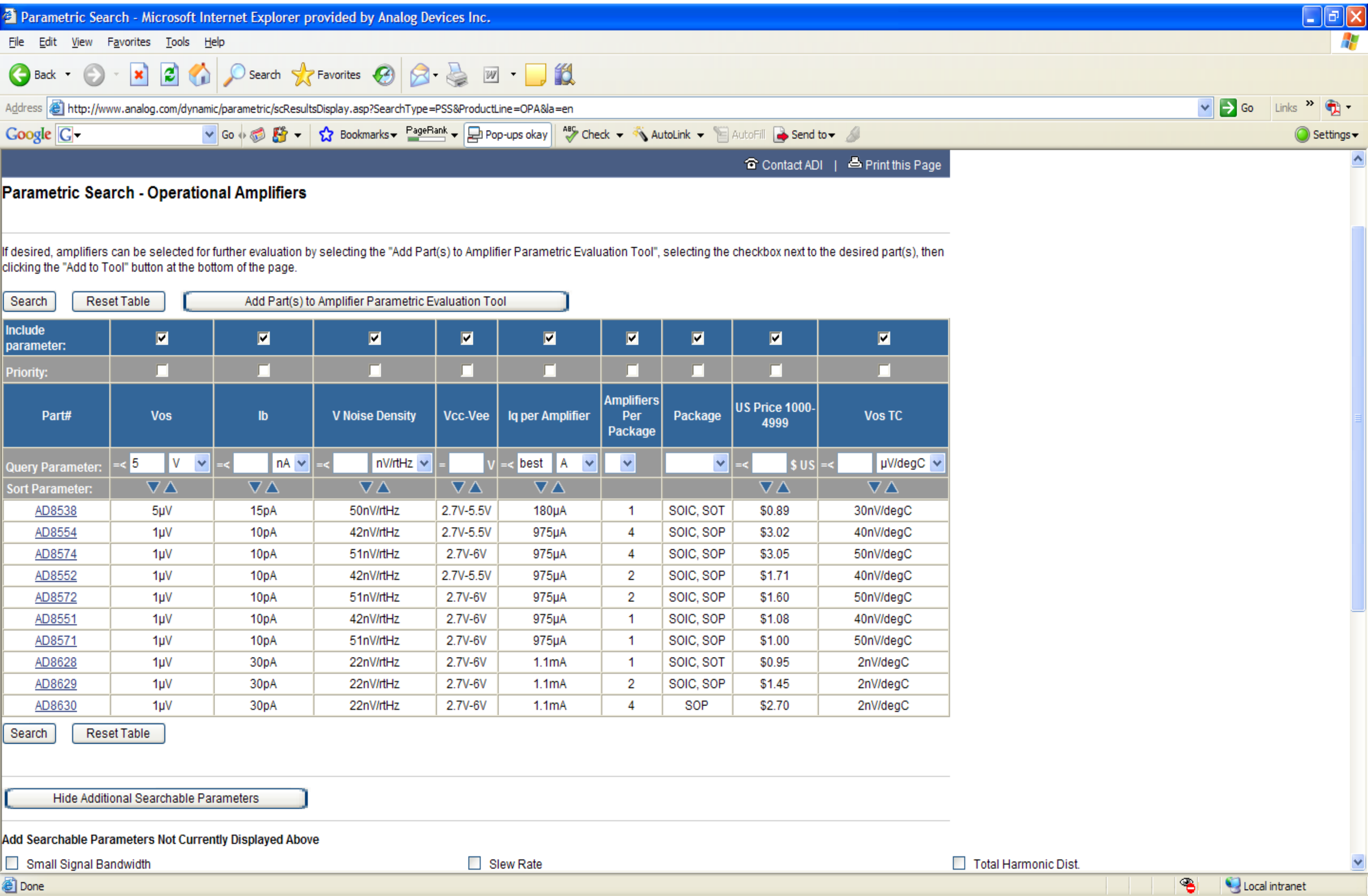
TPC 29. Current Noise Density vs. Frequency

Op Amp Specifications

Finding the best choice for low frequency applications

- **ADI's parametric search lets you search for op amps that meet the specs you need for:**
  - **Offset Voltage**
  - **Bias Current**
  - **Offset Voltage Drift**
  - **Low Frequency Current Noise**
  - **Low Frequency Voltage Noise**
  - **Input Capacitance**
  - **Input Impedance**
  - **Operating Temperature Range**
  - **And more …**





http://www.analog.com/dynamic/parametric/scResultsDisplay.asp?SearchType=PSS&ProductLine=OPA&la=en

Parametric Search - Operational Amplifiers

If desired, amplifiers can be selected for further evaluation by selecting the "Add Part(s) to Amplifier Parametric Evaluation Tool", selecting the checkbox next to the desired part(s), then clicking the "Add to Tool" button at the bottom of the page.

Search | Reset Table | Add Part(s) to Amplifier Parametric Evaluation Tool

Include parameter:	☑	☑	☑	☑	☑	☑	☑	☑	☑
Priority:	☐	☐	☐	☐	☐	☐	☐	☐	☐
Part#	Vos	Ib	V Noise Density	Vcc-Vee	Iq per Amplifier	Amplifiers Per Package	Package	US Price 1000-4999	Vos TC
Query Parameter:	=< 5 V	=< nA	=< nV/rtHz	= V	=< best A			=< $ US	=< µV/degC
Sort Parameter:	▽△	▽△	▽△	▽△	▽△			▽△	▽△
AD8538	5µV	15pA	50nV/rtHz	2.7V-5.5V	180µA	1	SOIC, SOT	$0.89	30nV/degC
AD8554	1µV	10pA	42nV/rtHz	2.7V-5.5V	975µA	4	SOIC, SOP	$3.02	40nV/degC
AD8574	1µV	10pA	51nV/rtHz	2.7V-6V	975µA	4	SOIC, SOP	$3.05	50nV/degC
AD8552	1µV	10pA	42nV/rtHz	2.7V-5.5V	975µA	2	SOIC, SOP	$1.71	40nV/degC
AD8572	1µV	10pA	51nV/rtHz	2.7V-6V	975µA	2	SOIC, SOP	$1.60	50nV/degC
AD8551	1µV	10pA	42nV/rtHz	2.7V-6V	975µA	1	SOIC, SOP	$1.08	40nV/degC
AD8571	1µV	10pA	51nV/rtHz	2.7V-6V	975µA	1	SOIC, SOP	$1.00	50nV/degC
AD8628	1µV	30pA	22nV/rtHz	2.7V-6V	1.1mA	1	SOIC, SOT	$0.95	2nV/degC
AD8629	1µV	30pA	22nV/rtHz	2.7V-6V	1.1mA	2	SOIC, SOP	$1.45	2nV/degC
AD8630	1µV	30pA	22nV/rtHz	2.7V-6V	1.1mA	4	SOP	$2.70	2nV/degC

Search | Reset Table

Hide Additional Searchable Parameters

Add Searchable Parameters Not Currently Displayed Above

☐ Small Signal Bandwidth ☐ Slew Rate ☐ Total Harmonic Dist.

AC Performance Specifications

- **Bandwidth**
- **Slew Rate**
- **Settling Time**
- **Phase Margin**
- **Noise**
- **Distortion**

Op Amp Specifications

Gain-bandwidth Product

- **The usable bandwidth of an amplifier depends on the gain for which it is configured**

- **Gain * Bandwidth = GBW product**
- **For example:**
  - **An amplifier has a** 1MHz **GBW product**
    - It only has a bandwidth of **10kHz** in a gain of **100** configuration

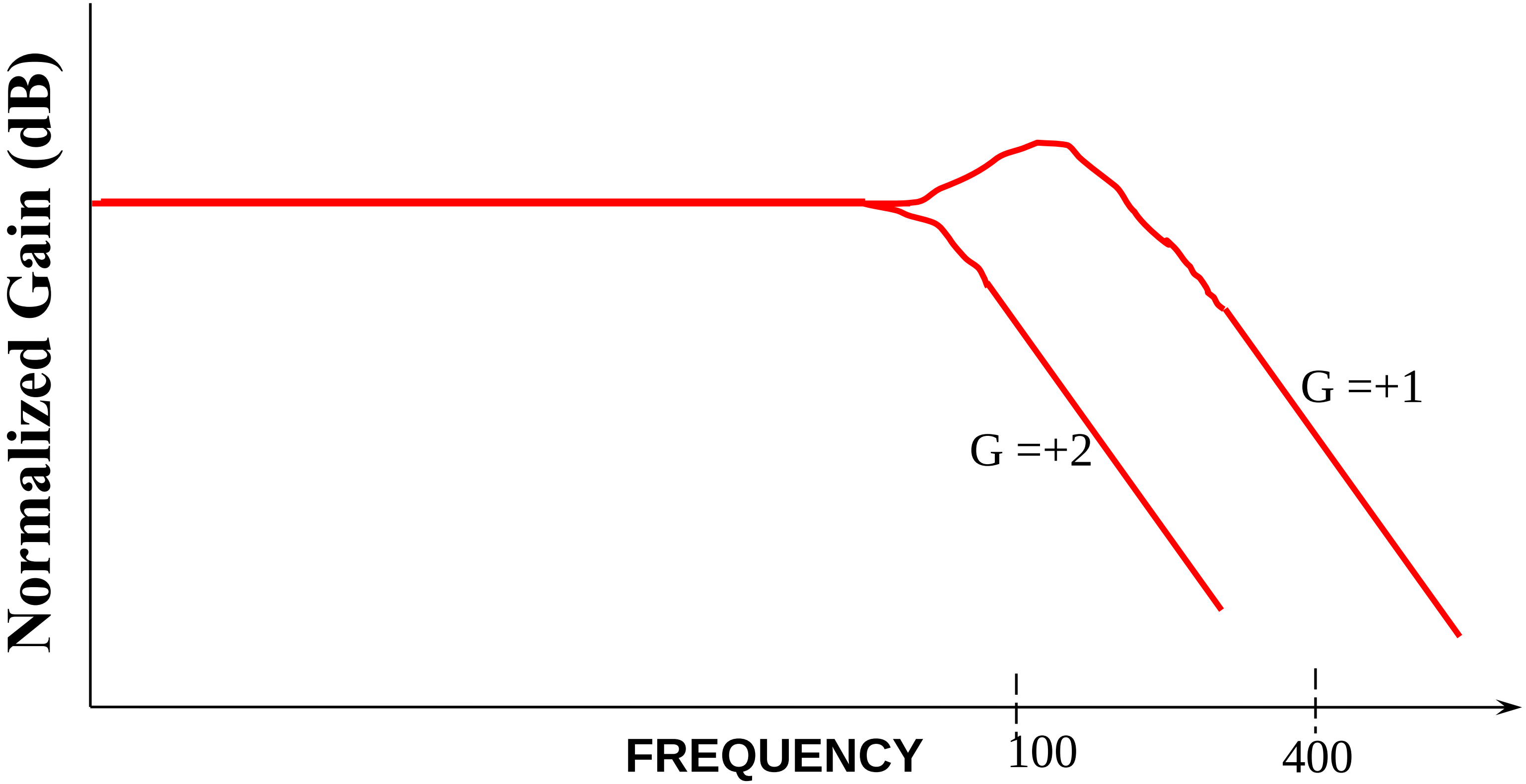
*** <u>Note: This is not true for current feedback amplifiers</u>**

3 Ways to Specify Bandwidth

- **-3dB bandwidth**
  - **Usually most favorable conditions**
  - **Small signal 0.2Vp-p or less – not slew limited**
  - **Can include some artificial bandwidth due to excessive peaking**
    - Gain of 2 bandwidth is less open for interpretation
- **-0.1dB flatness**
  - **Gain flatness over frequency**
  - **Critical in video applications**
- **Full-power bandwidth**
  - **Large signal; should be at least 2Vp-p**
  - **May be Slew Rate limited**
    - Full-power BW says nothing about distortion

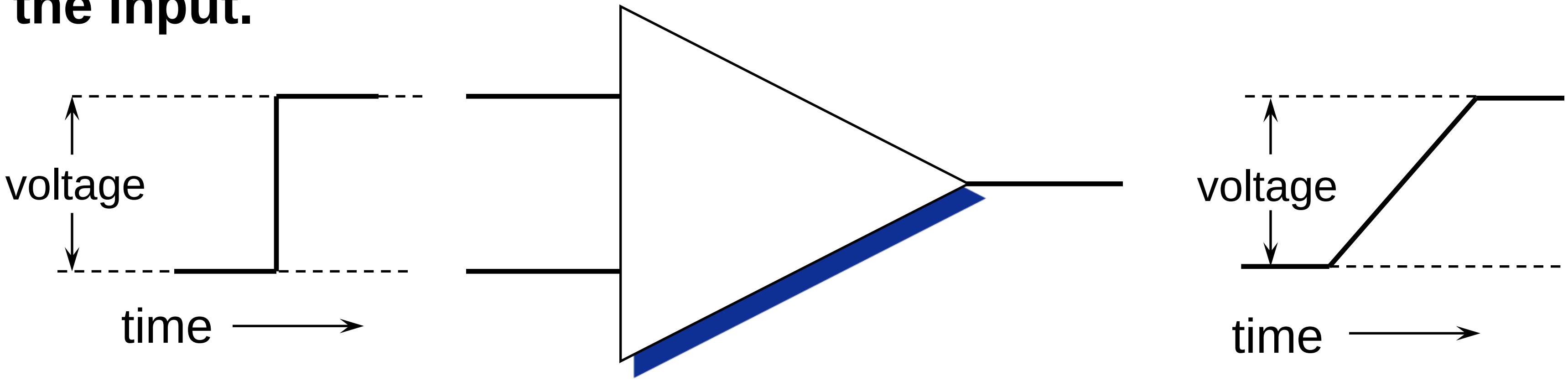
It is difficult to determine high-gain bandwidth from the front page!

- Peaking pulls the gain plot out in frequency
- Gain of +2 less than 1/2 Bandwidth of gain of +1 bandwidth
  - Gain bandwidth not constant

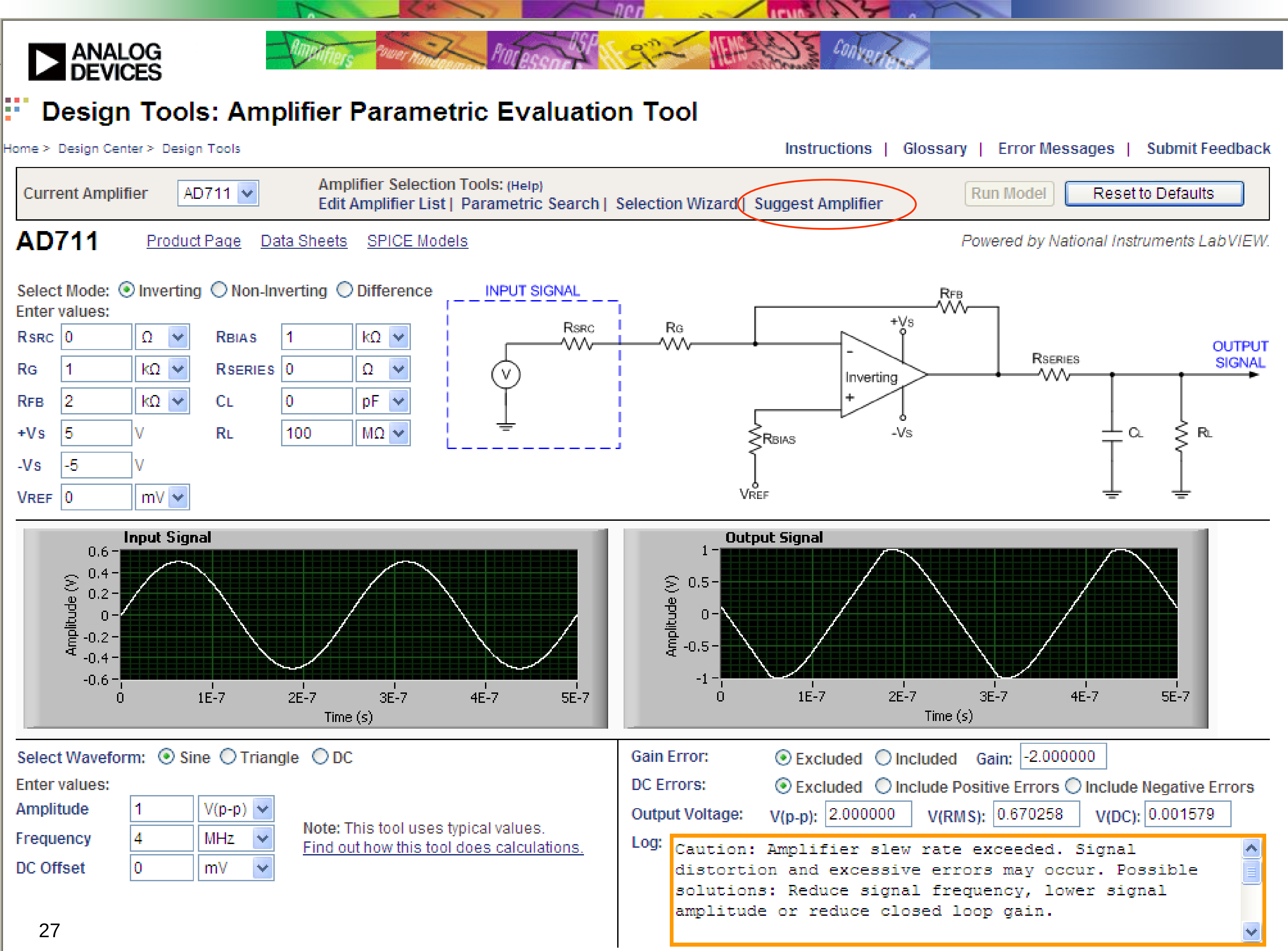


Slew Rate

Slew Rate is the maximum rate of change at an amplifier's output in response to a step change at the input.



Slew Rate is expressed in V/µs
When driving larger signals, slew rate limits bandwidth
F_{MAX} = (Slew Rate)/2πVpk



Design Tools: Amplifier Parametric Evaluation Tool

Current Amplifier: AD711

AD711

Powered by National Instruments LabVIEW.

Select Mode: ● Inverting ○ Non-Inverting ○ Difference

Enter values:

RSRC	0	Ω	RBIAS	1	kΩ
RG	1	kΩ	RSERIES	0	Ω
RFB	2	kΩ	CL	0	pF
+VS	5	V	RL	100	MΩ
-VS	-5	V			
VREF	0	mV			

Select Waveform: ● Sine ○ Triangle ○ DC

Enter values:

Amplitude	1	V(p-p)
Frequency	4	MHz
DC Offset	0	mV

Note: This tool uses typical values.
Find out how this tool does calculations.

Gain Error: ● Excluded ○ Included Gain: -2.000000

DC Errors: ● Excluded ○ Include Positive Errors ○ Include Negative Errors

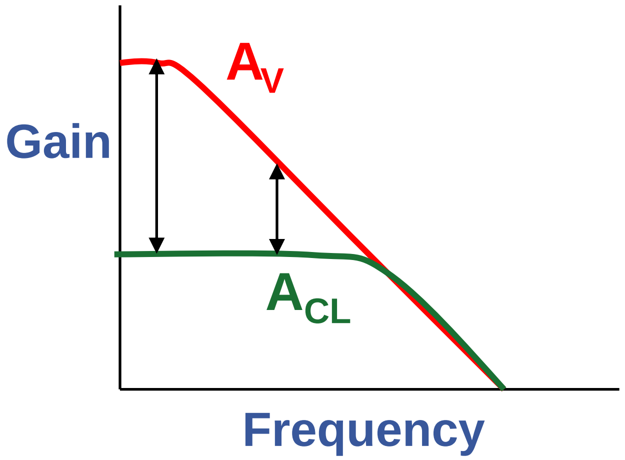
Output Voltage: V(p-p): 2.000000 V(RMS): 0.670258 V(DC): 0.001579

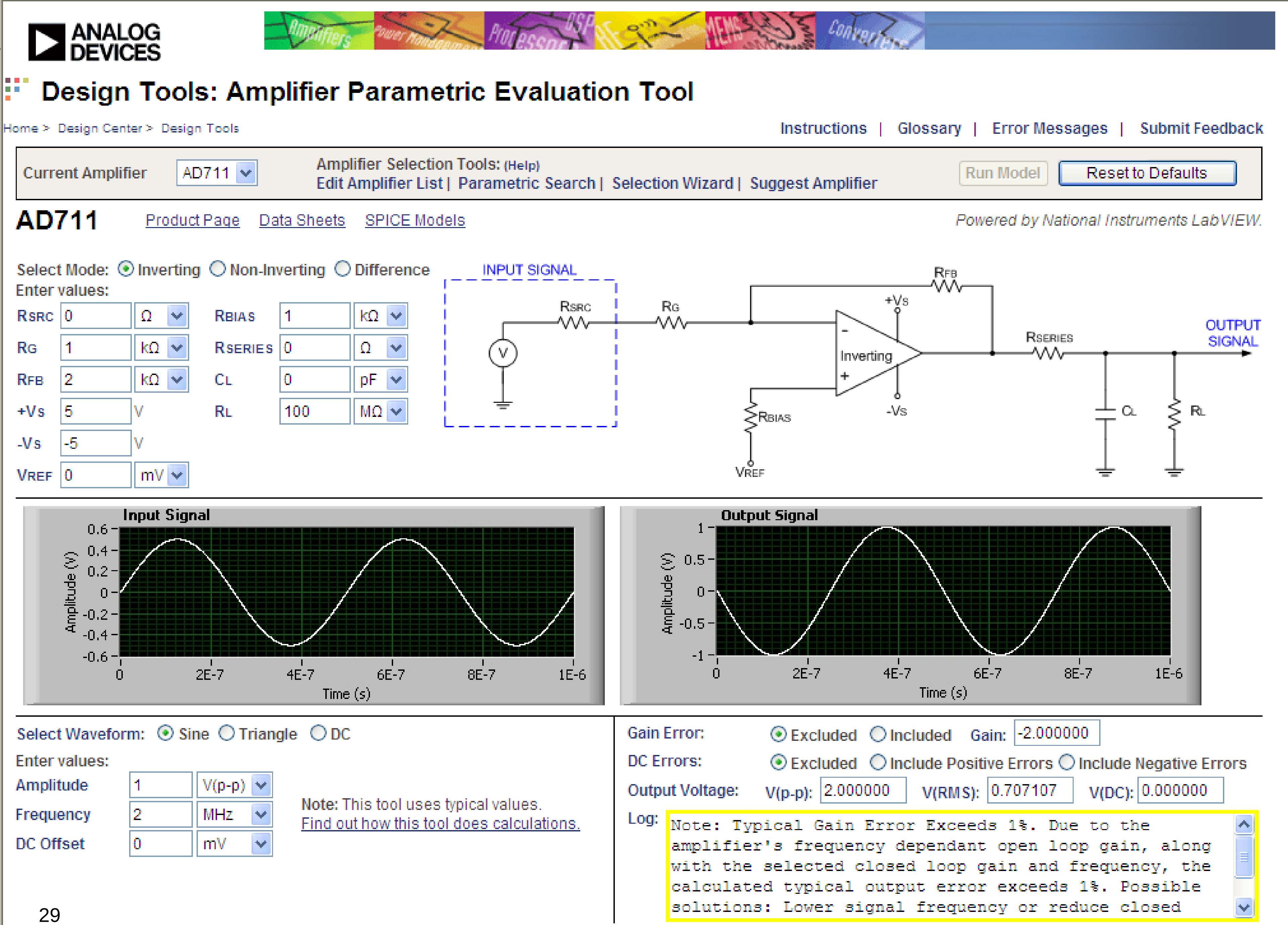
Log:

```
Caution: Amplifier slew rate exceeded. Signal
distortion and excessive errors may occur. Possible
solutions: Reduce signal frequency, lower signal
amplitude or reduce closed loop gain.
```

Bandwidth Requirements
Slew Rate & Loop Gain Error

- **When driving larger signals, slew rate limits bandwidth**
- **F_{MAX} = (Slew Rate)/2πVpk**
- **Rule of Thumb: Select amp with much higher BW than you think you need**
  - **Make sure slew rate can support this**
- **Why?**
- **Loop Gain Error:**
  - **A_{CL} not perfectly flat until it crosses A_V**
  - **Error in $A_{CL} = 1/(1+A_V/A_{CL})$**
  - **As A_{CL} gets closer to A_V, gain error rises**





Design Tools: Amplifier Parametric Evaluation Tool

Current Amplifier: AD711

AD711

Select Mode: ● Inverting ○ Non-Inverting ○ Difference

Enter values:

RSRC	0	Ω	RBIAS	1	kΩ
RG	1	kΩ	RSERIES	0	Ω
RFB	2	kΩ	CL	0	pF
+Vs	5	V	RL	100	MΩ
-Vs	-5	V			
VREF	0	mV			

Select Waveform: ● Sine ○ Triangle ○ DC

Enter values:

Amplitude	1	V(p-p)
Frequency	2	MHz
DC Offset	0	mV

Note: This tool uses typical values.
Find out how this tool does calculations.

Gain Error: ● Excluded ○ Included Gain: -2.000000

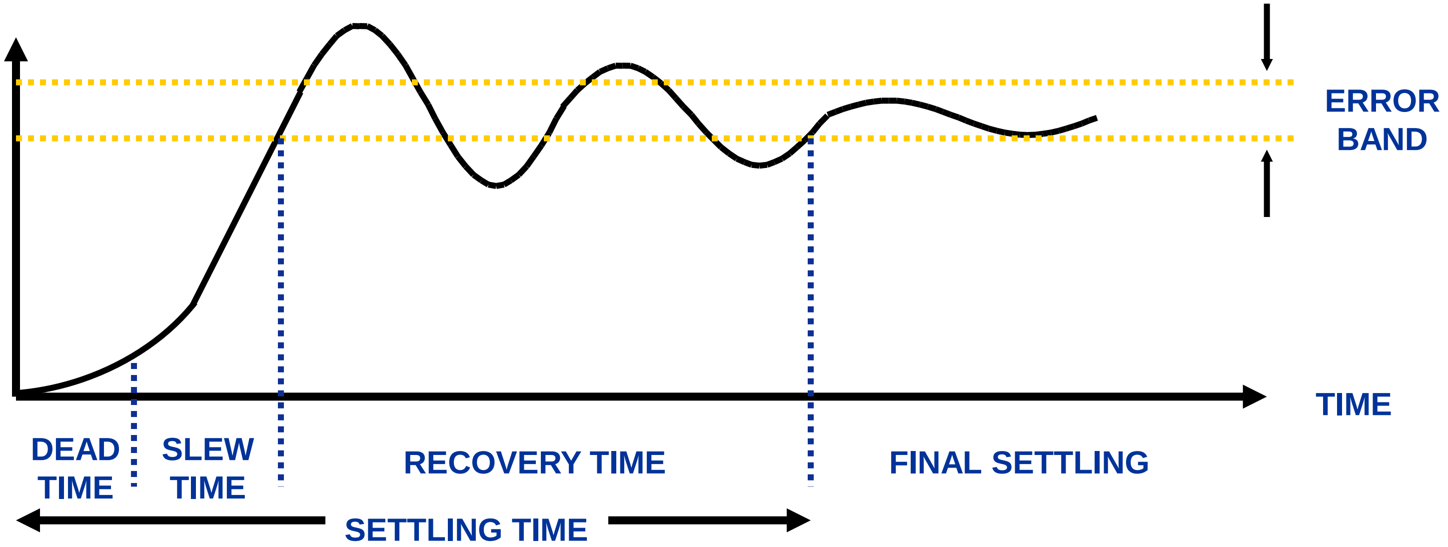
DC Errors: ● Excluded ○ Include Positive Errors ○ Include Negative Errors

Output Voltage: V(p-p): 2.000000 V(RMS): 0.707107 V(DC): 0.000000

Log:

```
Note: Typical Gain Error Exceeds 1%. Due to the
amplifier's frequency dependant open loop gain, along
with the selected closed loop gain and frequency, the
calculated typical output error exceeds 1%. Possible
solutions: Lower signal frequency or reduce closed
```

Settling Time



- **Settling time depends on:**
  - **The output step voltage, and**
  - **The settle to percentage of final value**
    - Output settles to 0.1%? 0.01%?
    - 0.1% accuracy is around 10 bits
- **Estimate settling time to N bits of accuracy:**

$t_S = 0.11(1+N)/f_{-3dB}$ **

AD8091 GBW product = 110MHz, @ G=25 BW =4.4MHz

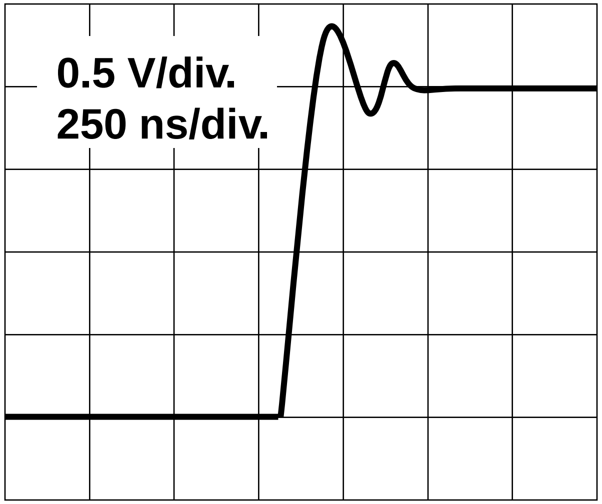
$t_S = 0.11(1+14)/4.4\text{MHz} = .375\mu s$

** valid if output amplitude rolls off @20dB/decade for at least 1 decade beyond f_{-3db}

Settling Time Graphs

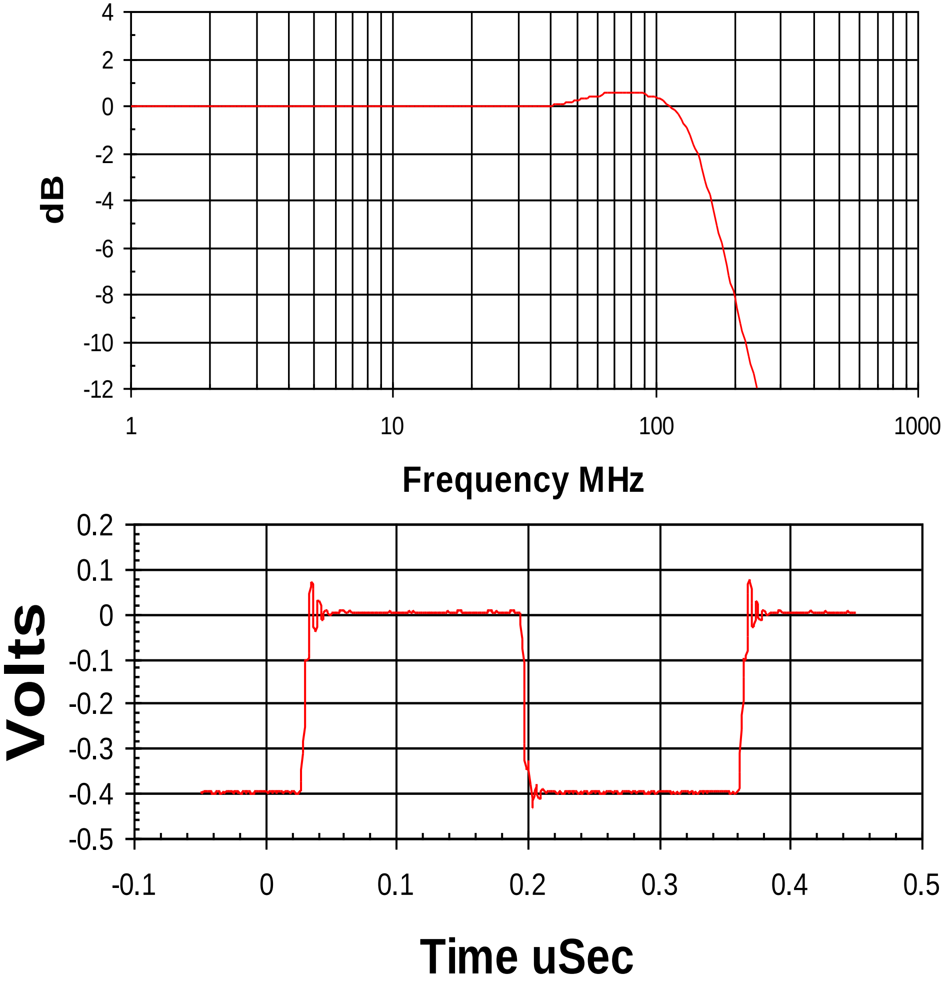
ELECTRICAL CHARACTERISTICS (V_S = ±**5.0V**, T_A= +25°C unless otherwise noted)

Parameter	Symbol	Conditions	Min	Typ	Max	Units
DYNAMIC PERFORMANCE						
Slew Rate	SR	$-4V < V_{OUT} < 4V$, $R_L = 10k\Omega$		13		V/µs
Gain Bandwidth Product	GBP			15		MHz
Phase Margin	Øo			64		degrees
Settling Time	t_S	To 0.1%, $A_V = -1$, V_O = 2V Step		475		ns



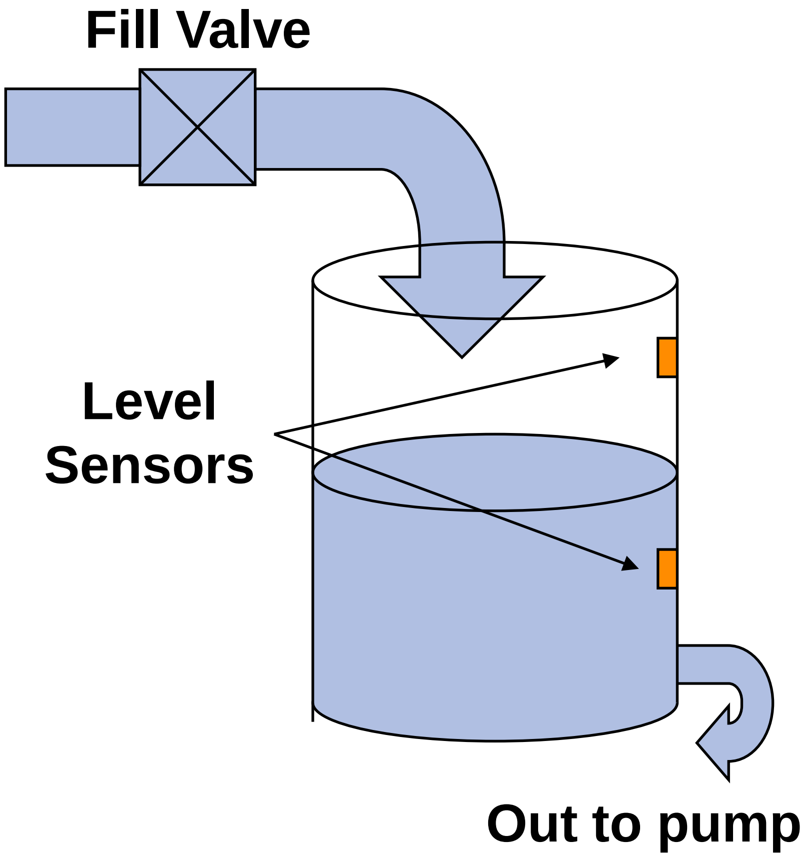
Why Phase Margin is Important

- **Peaking in the Frequency Domain causes Ringing in the Time Domain As a result of Low Phase Margin**



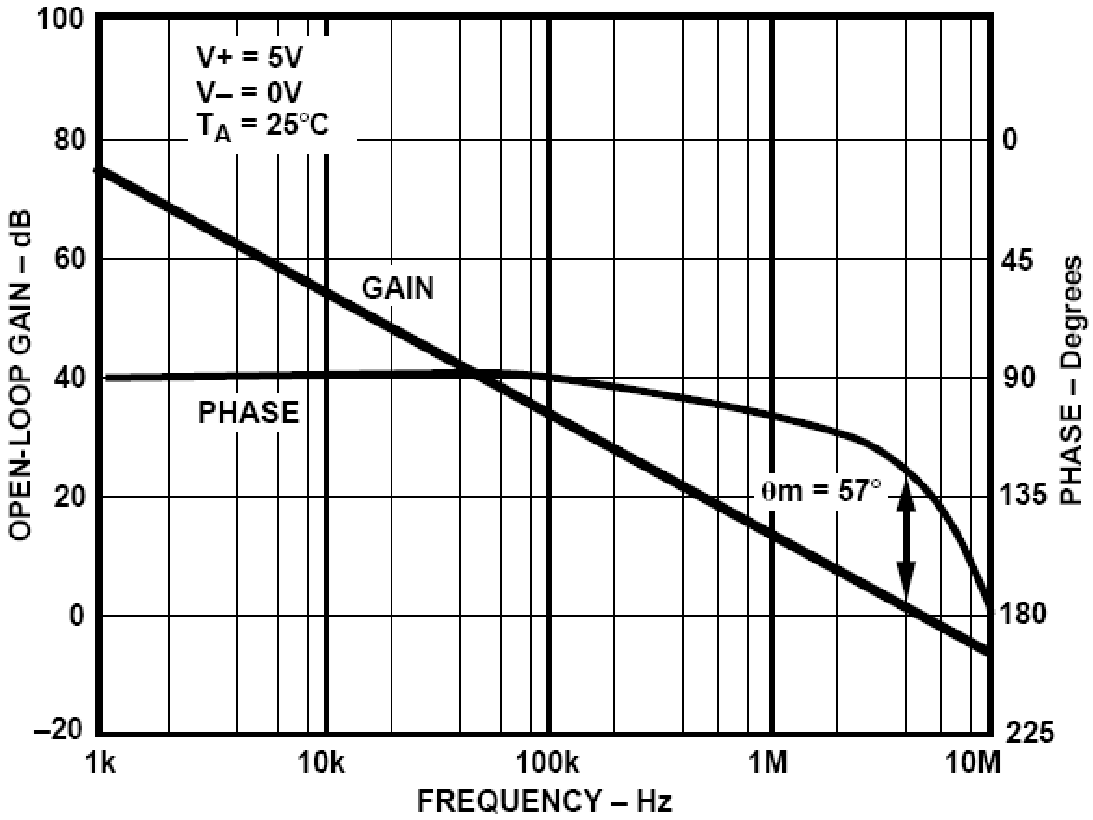
Phase Margin

- Any closed loop system has phase margin
  - Including closed-loop op amps
- Example Application:
  - A reservoir tank is supplied by a large valve
  - The goal is to keep some water in the tank without overflowing
  - Sensors determine when valve needs to open or close



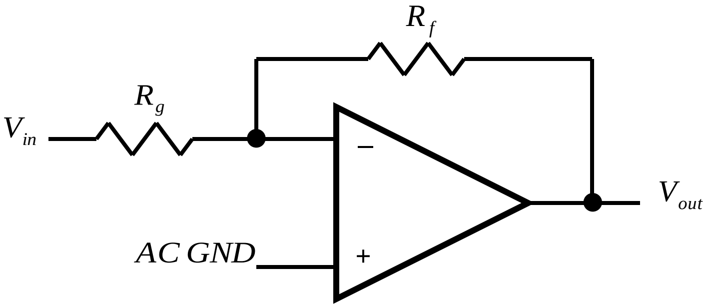
Relation Between Open Loop Gain and Phase

- **Phase Margin - Phase Remaining before the Phase Delay through the Amp Reaches 180 degrees**
  - **Margin of Less than 30 degrees can be a Problem**



Standard Current Feedback Amplifier Configurations

Inverting Amplifier

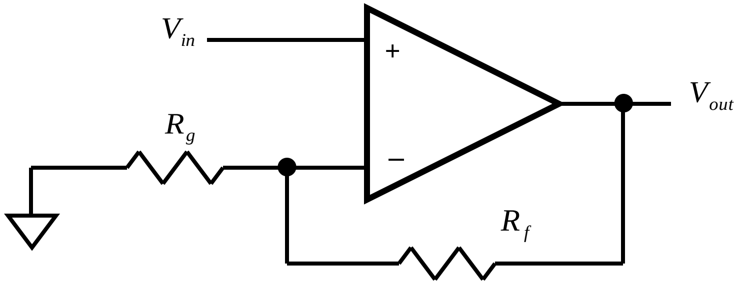


$$\frac{V_{out}}{V_{in}} = \left(\frac{-R_f}{R_g}\right)\left[\frac{1}{1+\dfrac{R_f\left(1+\dfrac{R_O}{R_f}+\dfrac{R_O}{R_g}\right)}{Z(s)}}\right]$$

If $R_o << R_{f,g}$:

$$\boxed{\frac{V_{out}}{V_{in}} = \left(\frac{-R_f}{R_g}\right)\left[\frac{1}{1+\dfrac{R_f}{Z(s)}}\right]}$$

Non-Inverting Amplifier



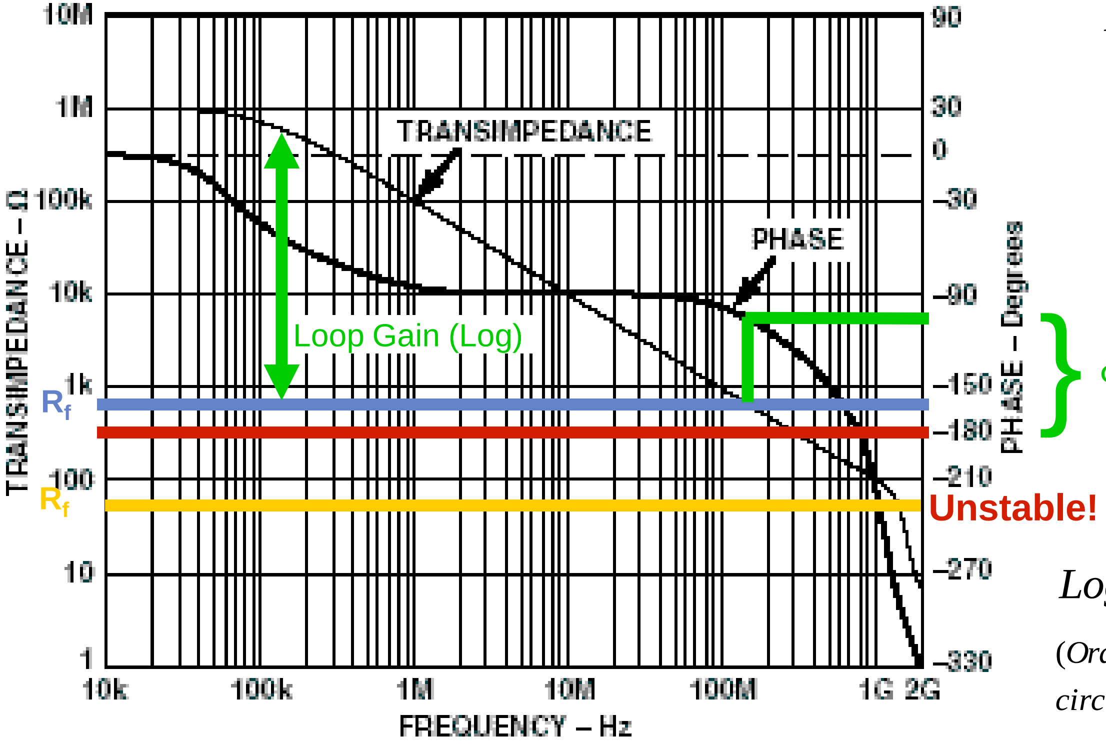
$$\frac{V_{out}}{V_{in}} = \left(1+\frac{R_f}{R_g}\right)\left[\frac{1}{1+\dfrac{R_f\left(1+\dfrac{R_O}{R_f}+\dfrac{R_O}{R_g}\right)}{Z(s)}}\right]$$

If $R_o << R_{f,g}$:

$$\boxed{\frac{V_{out}}{V_{in}} = \left(1+\frac{R_f}{R_g}\right)\left[\frac{1}{1+\dfrac{R_f}{Z(s)}}\right]}$$

Current CFB Amplifier Stability Analysis

Case In Point – AD8007



TPC 10. Transimpedance and Phase vs. Frequency

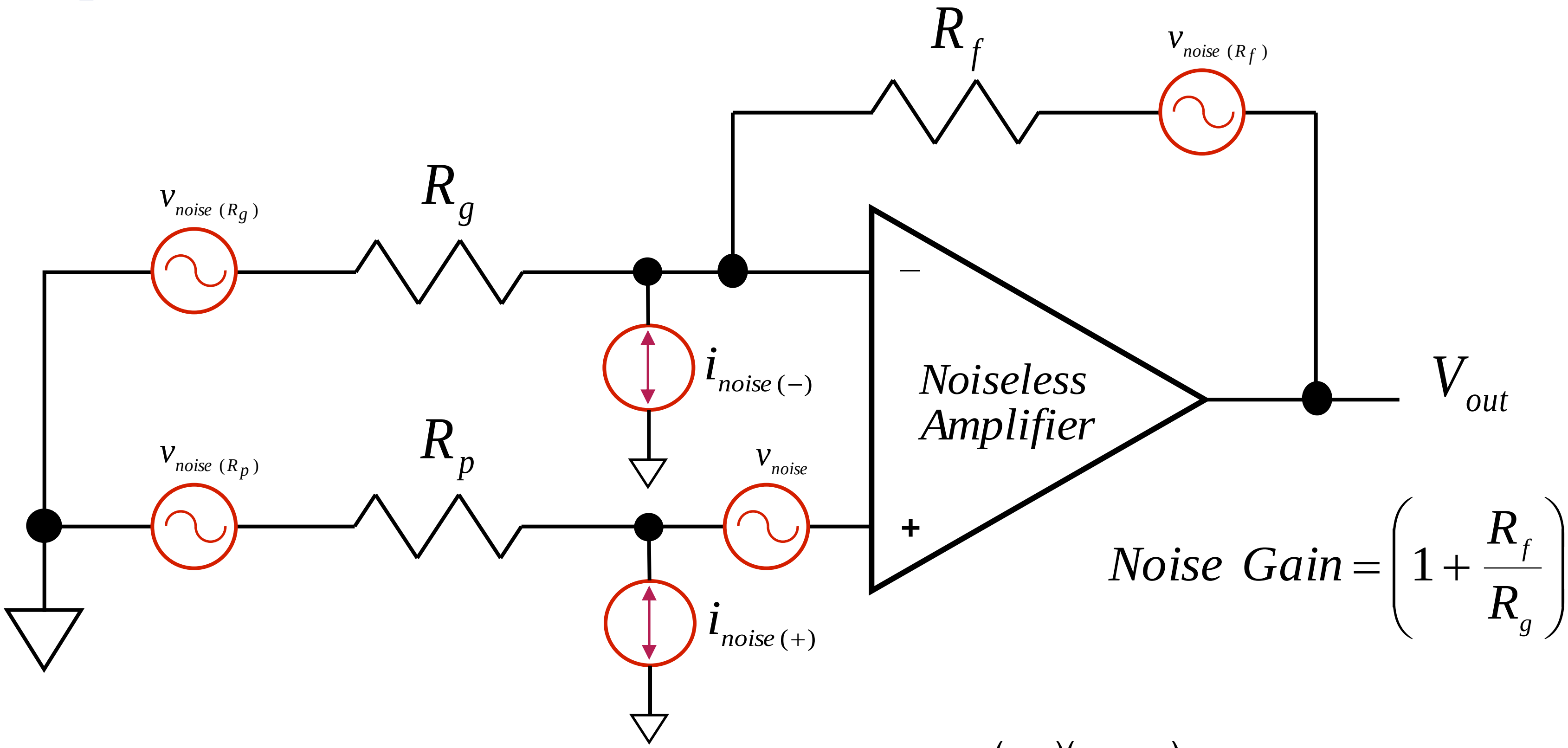
$$Loop\ Gain = \frac{Z(s)}{R_f\left(1 + \frac{R_O}{R_f} + \frac{R_O}{R_g}\right)}$$

$$\left|Loop\ Gain\right|_{Neglecting R_O} = \frac{\left|Z(s)\right|}{R_f}$$

$$Log_{10}\left|Loop\ Gain\right| = Log_{10}\left|Z(s)\right| - Log_{10}\left(R_f\right)$$

(Ordinate could be calibrated in dB w/ respect to 1Ω to circumvent difficulty of taking the log of an impedance.)

Amplifier Noise Sources



$$Noise\ Gain = \left(1 + \frac{R_f}{R_g}\right)$$

$$Output\ Noise\ Due\ To\ Inverting\ Input\ Current\ Noise = (R_f)(i_{noise(-)})$$

$$Output\ Noise\ Due\ To\ R_f\ Noise = \sqrt{4kTR_f}$$

$$Output\ Noise\ Due\ To\ Input-referred\ Voltage\ Noise = (v_{noise})(Noise\ Gain)$$

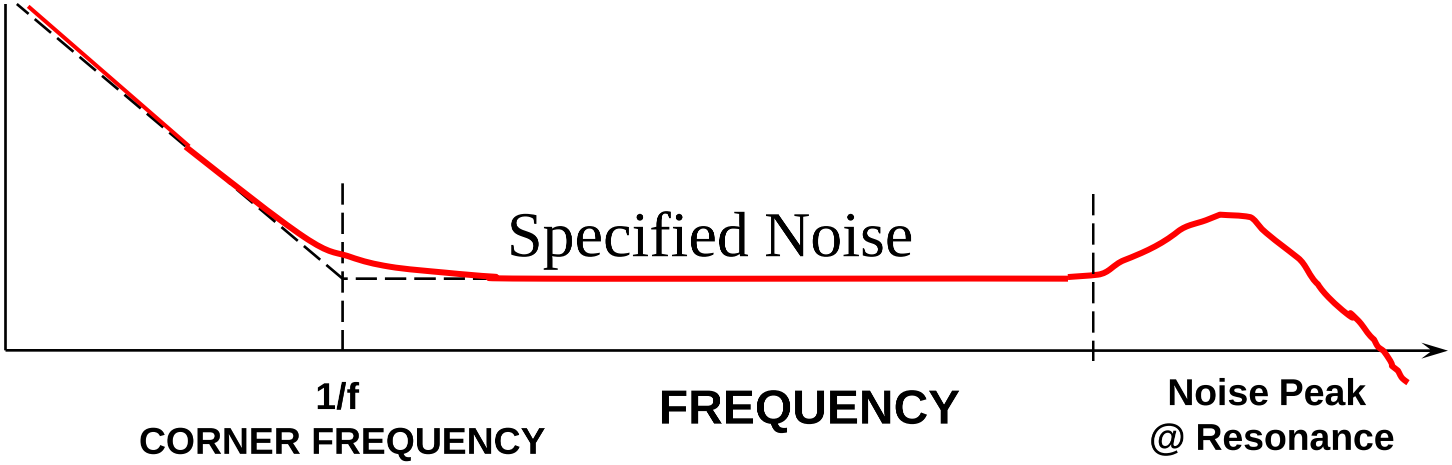
$$Output\ Noise\ Due\ To\ Non-Inverting\ Input\ Current\ Noise = (i_{noise(+)})(R_p)(Noise\ Gain)$$

$$Output\ Noise\ Due\ To\ R_g\ Noise = \left(\sqrt{4kTR_g}\right)\left(\frac{R_f}{R_g}\right)$$

$$Output\ Noise\ Due\ To\ R_p\ Noise = \left(\sqrt{4kTR_p}\right)(Noise\ Gain)$$

High Frequency Noise

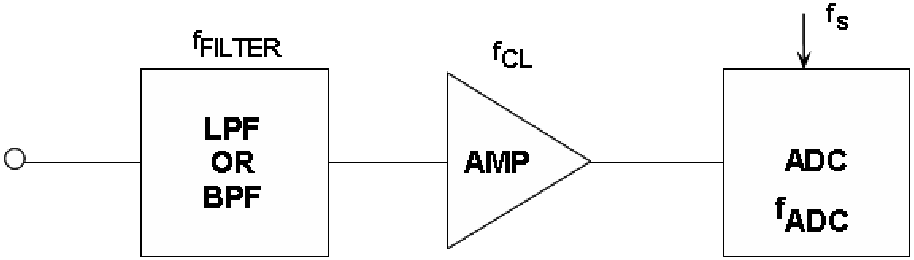
- **Low Noise Amplifiers Are Characterized By...**
  - Low Voltage Noise Densities, e_n : < 10 nV / √Hz
  - Low Current Noise Densities, i_n : < 10 fA / √Hz
- **Noise is usually specified in some frequency band**
  - e.g. 100 Hz to 10MHz
- **Noise can peak near resonances**
  - Total noise may be higher than can be determined from simple calculations



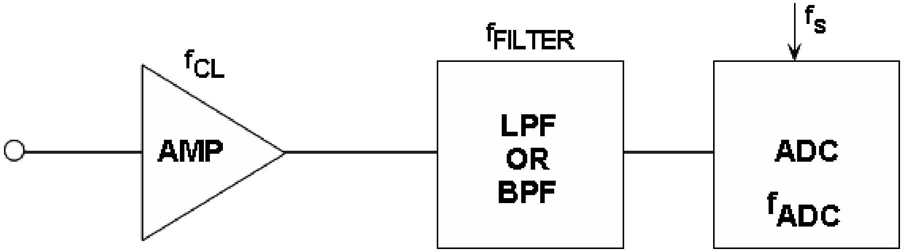
Noise

Combining sources

- Uncorrelated noise sources combine root-sum-square:
- Total Noise = $\sqrt{(E_N^2 + I_{N-}^2 + N_{RF}^2 + N_{RI}^2)}$
- Reducing effect of amplifier noise:



AMP NOISE INTEGRATED
OVER f_{CL} OR f_{ADC},
WHICHEVER IS LESS



AMP NOISE INTEGRATED
OVER FILTER BW, f_{FILTER}

IN GENERAL, $f_{FILTER} < \frac{f_S}{2} \ll f_{ADC} < f_{CL}$

Distortion

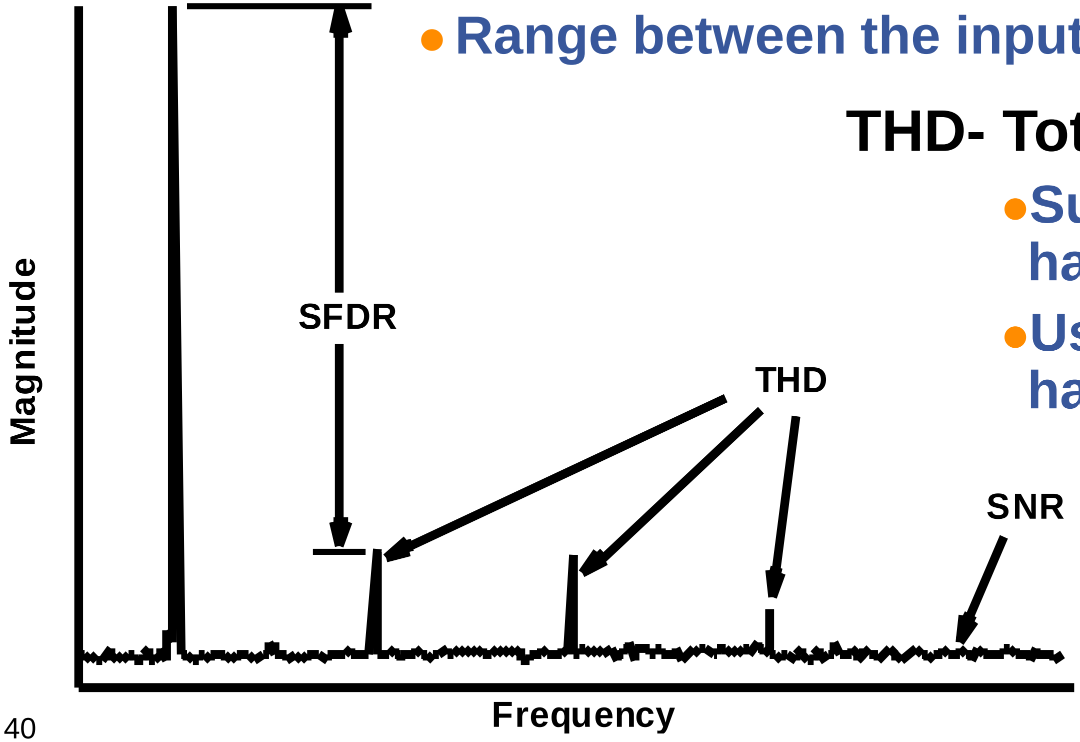
- Changes in the output wave form relative to the input wave form
  - For pure sine wave in the output will have some energy at multiple of the input frequency - harmonics

SFDR - used for communications and other systems

- Spurious-free Dynamic Range in dB
- Range between the input signal and largest spurs

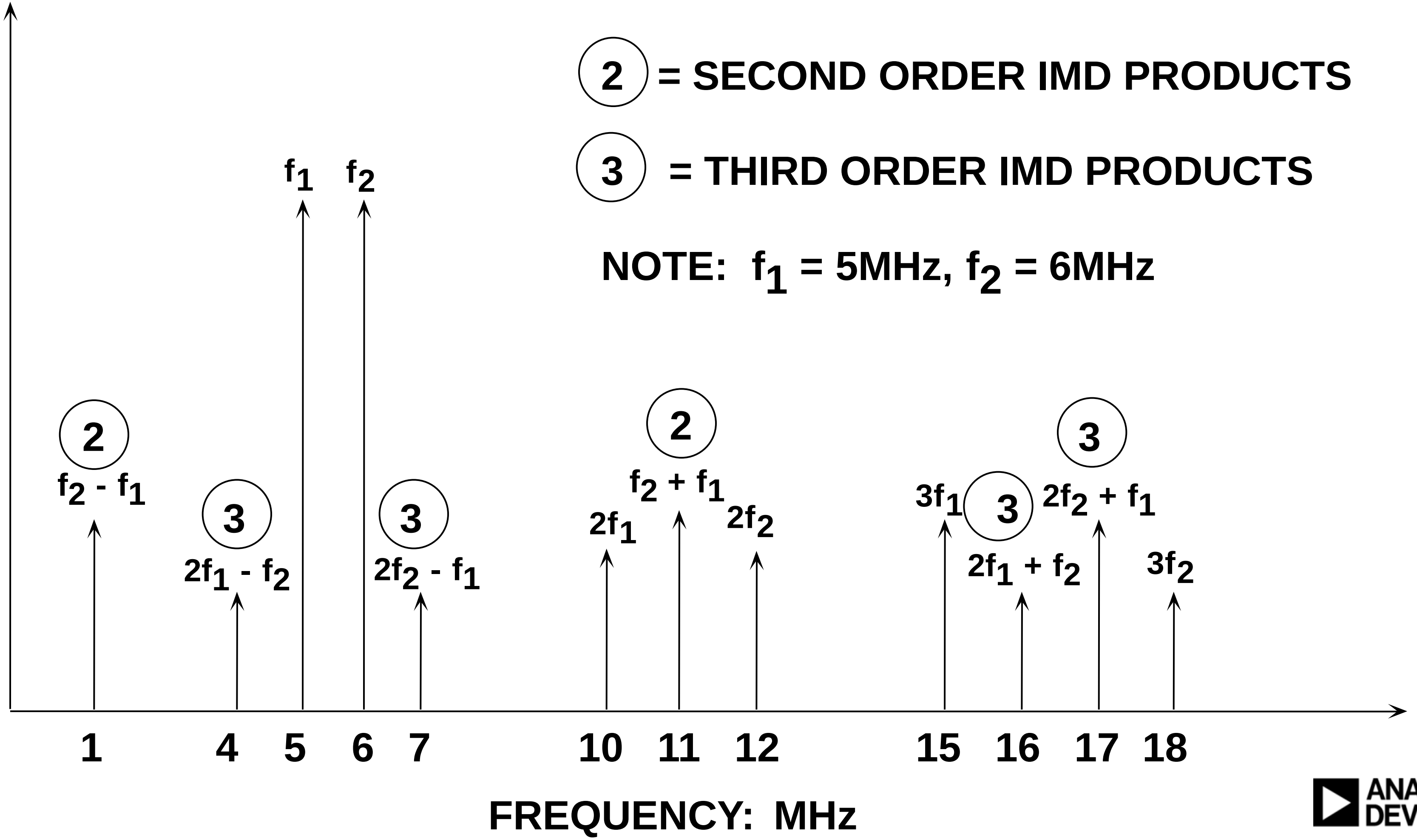
THD- Total Harmonic Distortion

- Sum of all distortions at all harmonics
- Usually 2nd and 3rd harmonics contribute the most



IMD and IP3

- IMD (Intermodulation Distortion [dB])
  - Output Signal Energy Resulting from 2 Signal Frequencies (f1 and f2) that are Close together When Applied at the Input



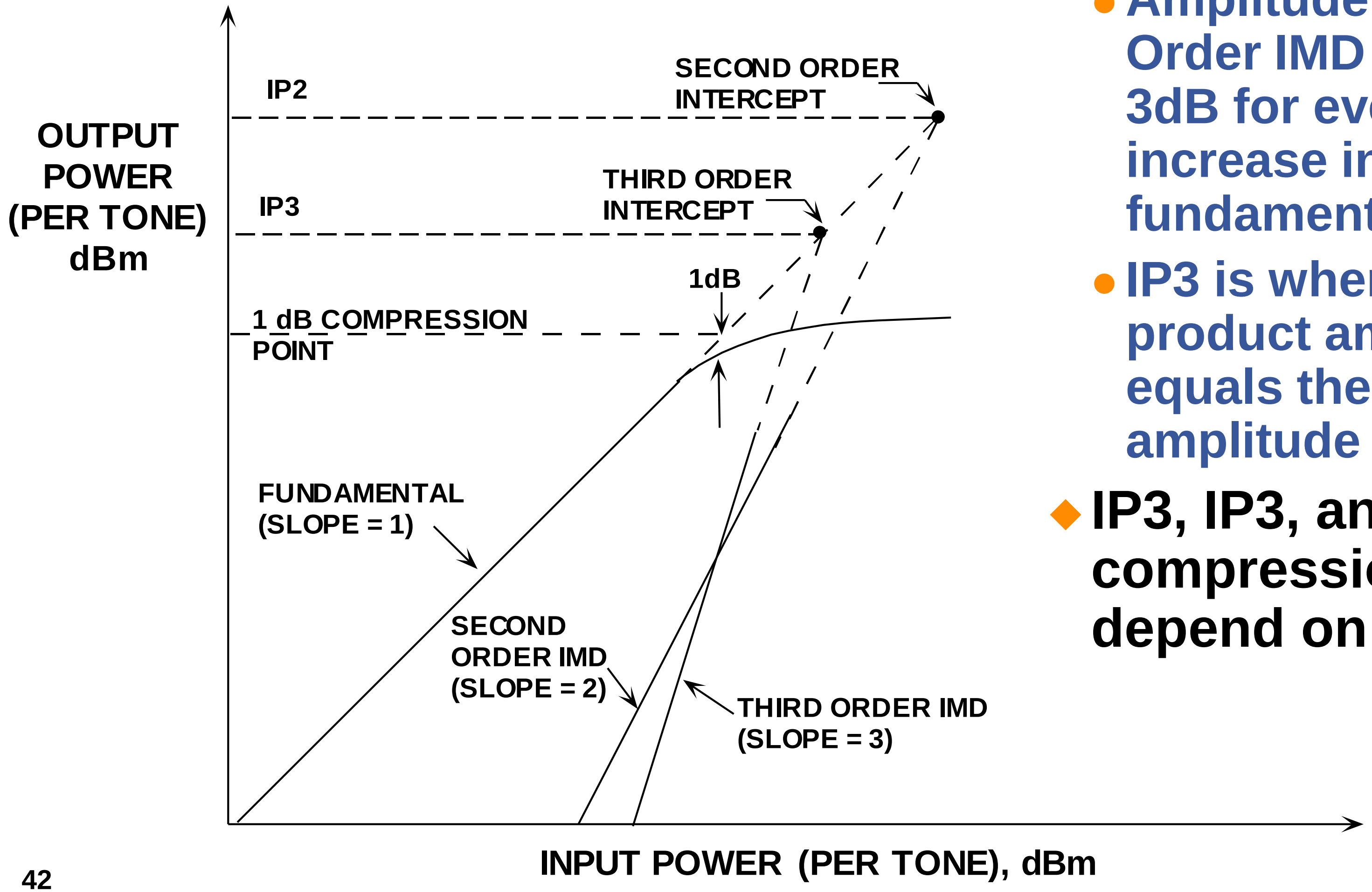
② = SECOND ORDER IMD PRODUCTS

③ = THIRD ORDER IMD PRODUCTS

NOTE: f_1 = 5MHz, f_2 = 6MHz

INTERCEPT POINTS AND 1dB COMPRESSION POINT

- IP3 (Third order intercept) characterizes third order IMD

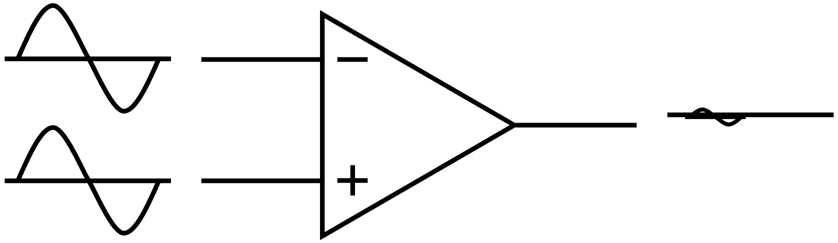


  - Amplitude of Third Order IMD increases 3dB for every 1dB increase in amplitude of fundamental
  - IP3 is where IMD product amplitude equals the fundamental amplitude
- IP3, IP3, and 1dB compression point depend on frequency

Additional Op Amp Performance Specs

- CMRR
- PSRR
- Crosstalk
- Input Common Mode Range
- Rail-to-Rail Requirements
- Low Power Applications

Common Mode Rejection Ratio (CMRR)

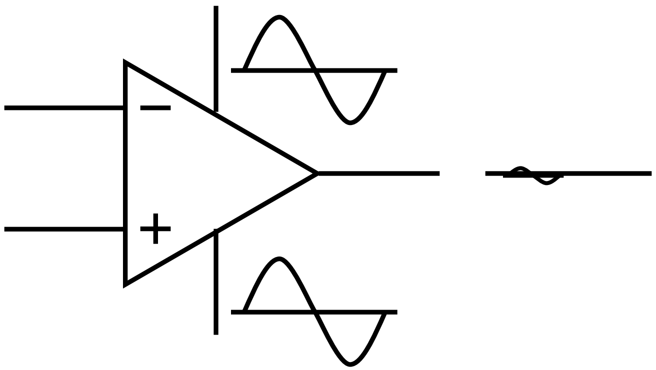


- Adm is the differential mode gain, which ideally is infinite
- Acm is the common mode gain, which ideally is zero

$$CMRR = 20\log\left|\frac{Adm}{Acm}\right|$$

- CMRR is important in non-inverting, difference or instrumentation amplifiers
- Inverting amplifier configurations are not (there is no common mode voltage)

Power Supply Rejection Ratio (PSRR)



- ❑The power supply pins of an amplifier are signal inputs (i.e. supply voltages). The ability of the amplifier to reject noise and unwanted signals present on the power supply line is important!

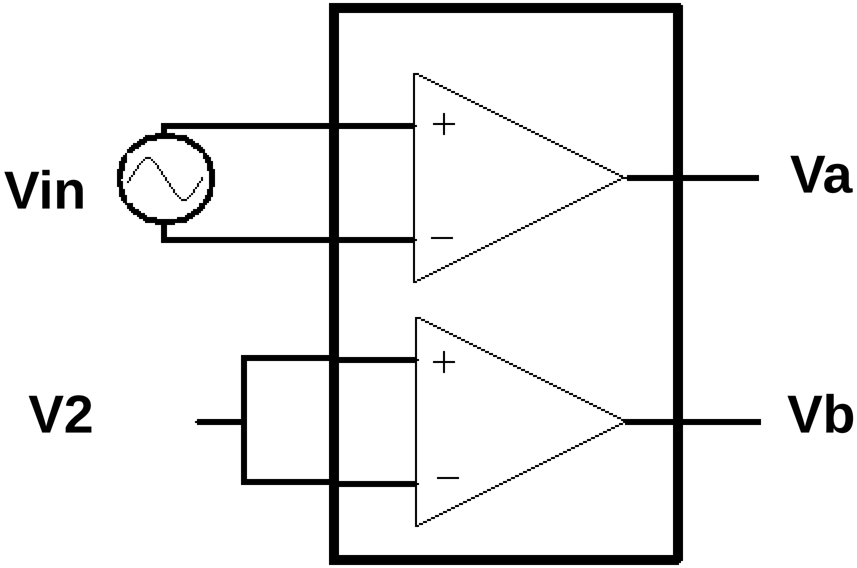
$$PSRR = 20\log\left|\frac{\Delta Vio}{\Delta Vs}\right|$$

Where

- ❑ ΔVio is the change at the output, referred back to the input
- ❑ ΔVs is the increment of the supply voltage change

Crosstalk

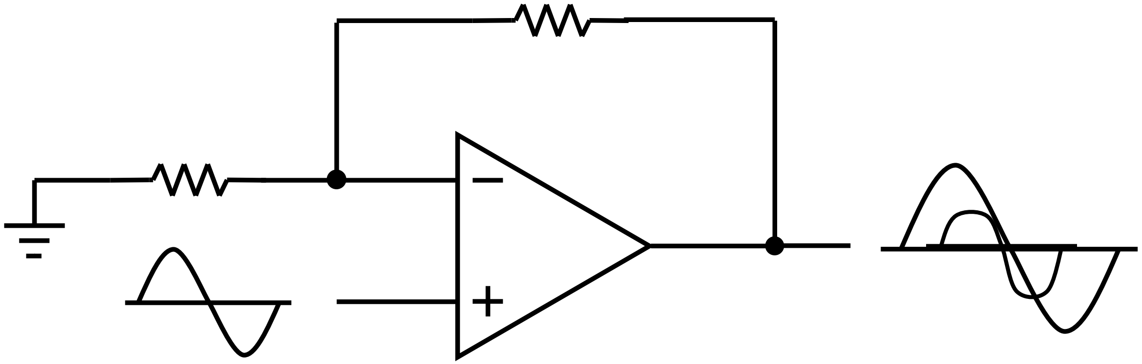
- Specification for multi-channel devices
- Measure of how much “information” from a channel is seen in another channel
- Normally specified when gain and configuration on each channel is equal
  - Otherwise Crosstalk may be different
- Typically specified in dB



How much of the output Va do you see on output Vb?

Also, how much of input Vin is seen on output Vb?

Input Common Mode Voltage Range

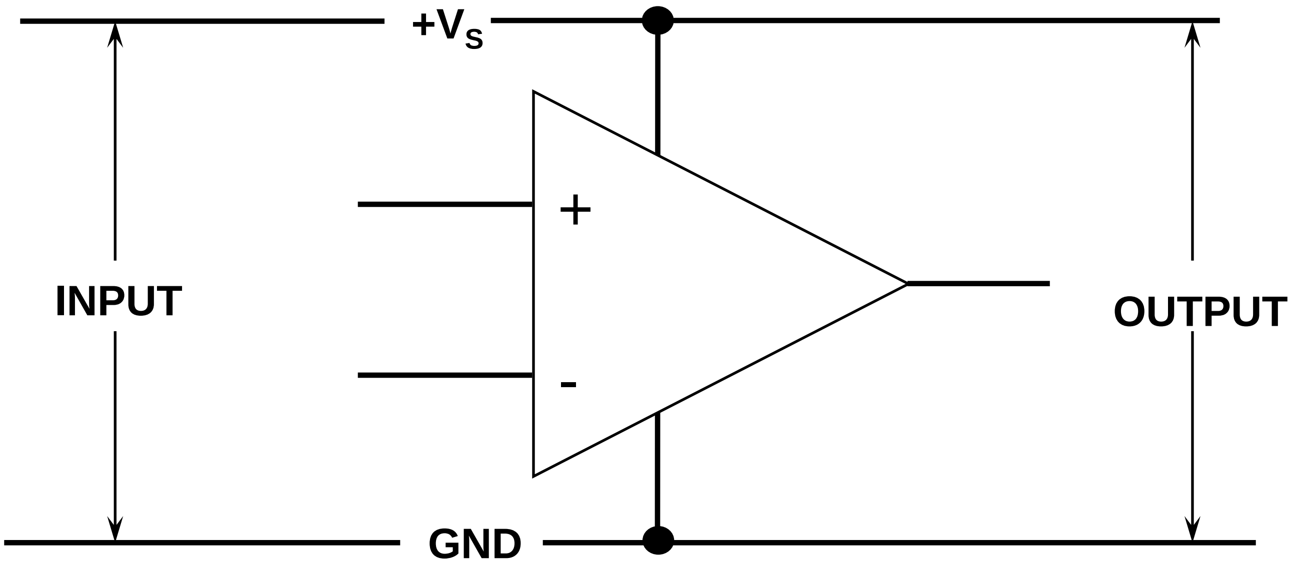


- ☐ Input Common Mode Voltage Range is the maximum range the input can swing and still operate in the specified limits of the amplifier.

- ☐ Exceeding the Input Common Mode Voltage Range can cause the amplifier to distort the input signal or even damage the amplifier!

Rail to Rail Amplifiers

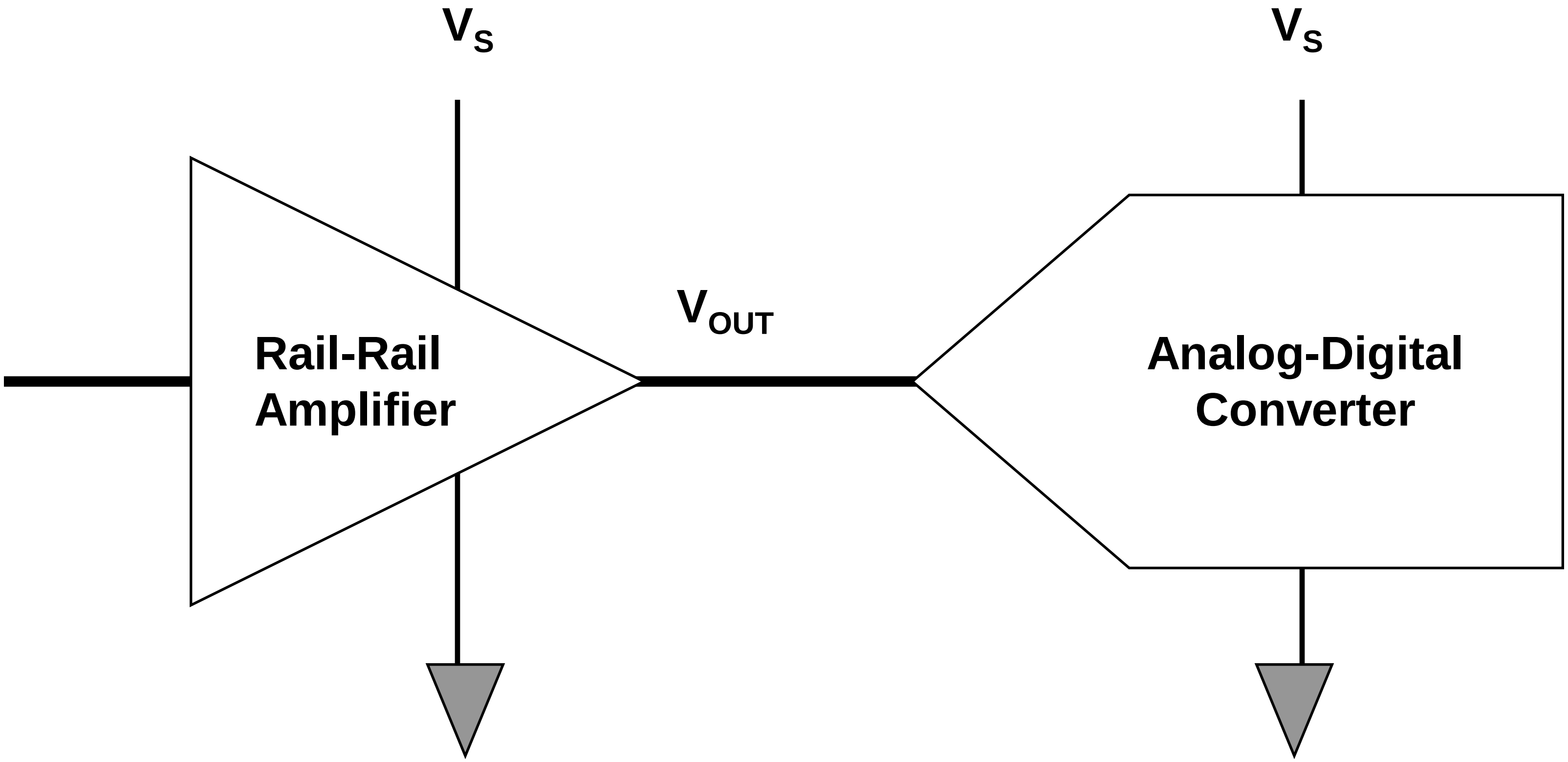
What is a Rail-Rail Amplifier?



True Rail-Rail Op Amp

- True Rail-Rail Op Amps Can Swing to Within a Few mV of Their Power Supply Rails, Either on the Input, the Output or Both

Why Use a Rail-to-Rail Amplifier?



- Rail-to-rail amplifiers maximize signal swing between the supply voltages
- Many high speed A-D converters operate from single +3V to +5V supply

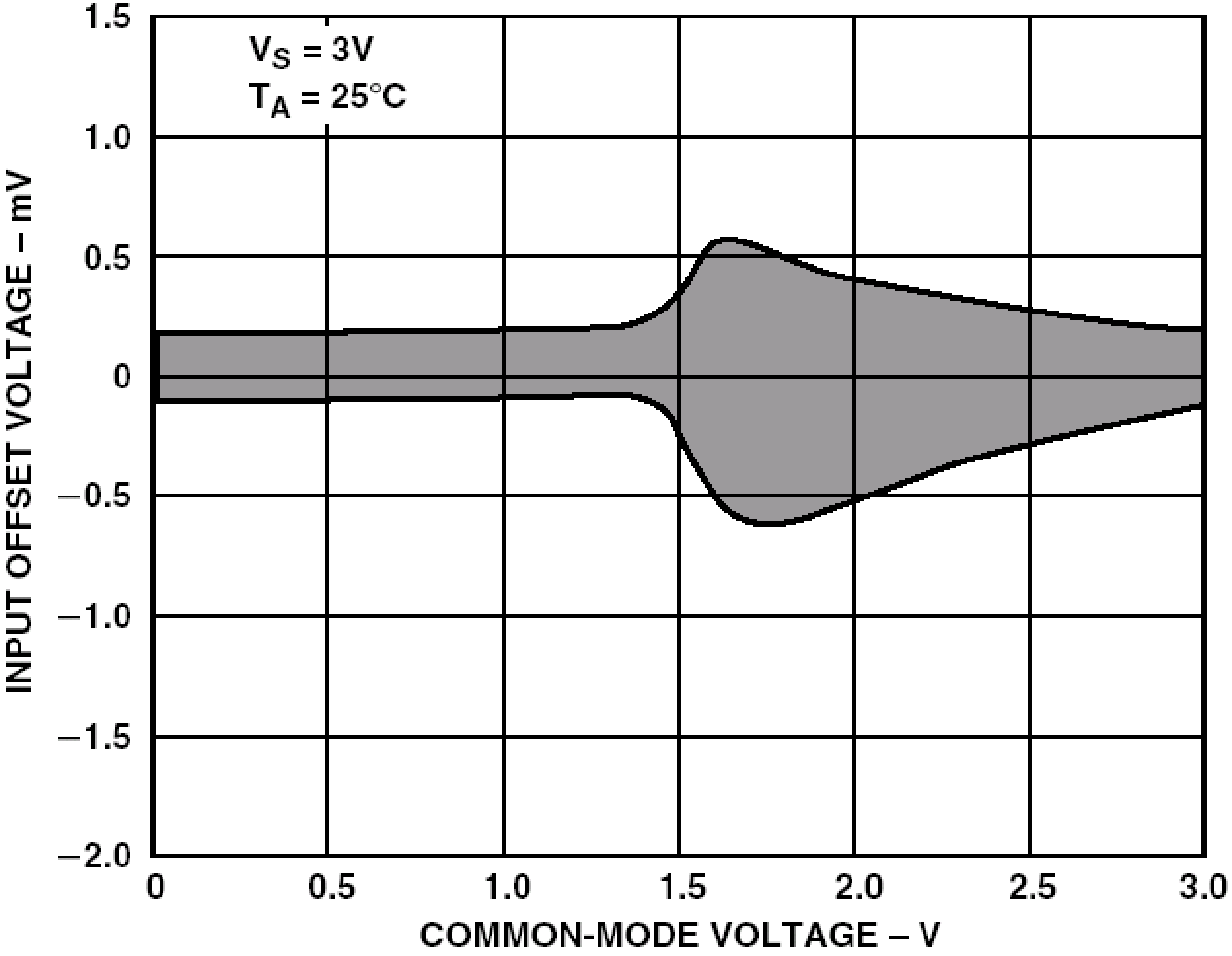
When is Rail-to-Rail Input Needed?

- Unity-gain buffer applications that require the maximum input signal range
  - Example: A unity-gain buffer driving a +3V ADC
- Applications where the input common-mode range is near the voltage supply
  - Example: High-side current monitor amplifier

Rail-to-Rail Input Issues

- Offset voltage will vary over the input common-mode range
  - Could result in low CMRR at certain V_{CM}
- Possible increase in cross-over distortion
- In bipolar input stage: Input bias current will switch direction!
  - At high V_{CM}, bias current flows into the inputs
  - At low V_{CM}, bias current flows out of the inputs
- Tip: Use an input bias correction resistor to minimize output error

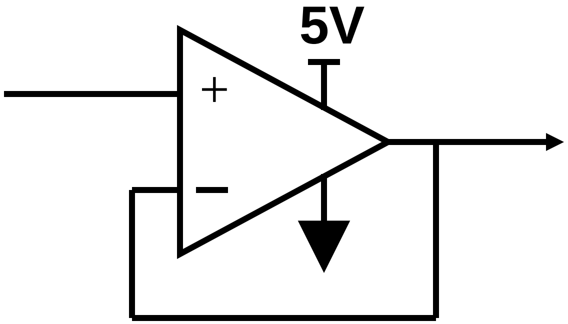
Offset Voltage May Change Significantly Across V_{CM} Range of R-R Input!



Sometimes a Rail-to-Rail Input is NOT Needed!

Consider:

V_{IN}
0V to 5V

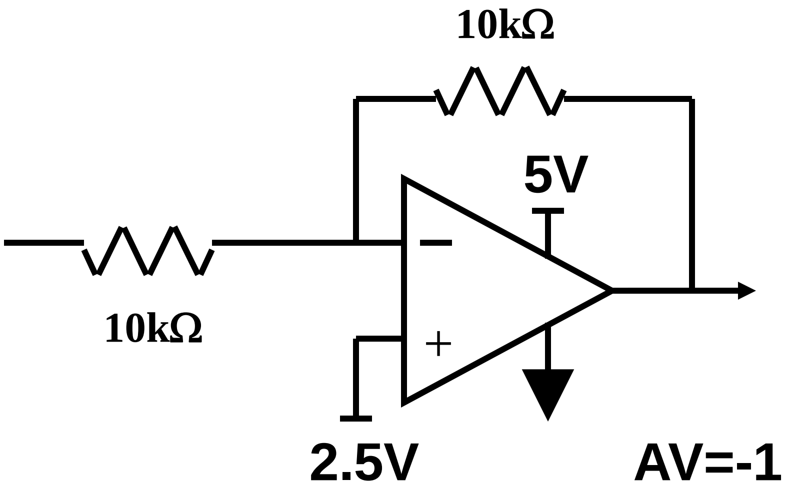


To
ADC Input

V_{OUT}=
0V to 5V

Is the same as:

V_{IN}
0V to 5V



AV=-1

V_{OUT}=
5V to 0V

Rail-to-Rail Input Not Needed!

Rail-to-Rail Output Amplifiers

- Output Saturation Voltage is defined as how close the output can get to a supply rail
- In rail-to-rail output amplifiers, $V_{OUT,MAX}$ will vary with output current and supply voltage
- Higher I_{OUT} means the output voltage cannot get as close to the supply rails
  - Both for sourcing and sinking current

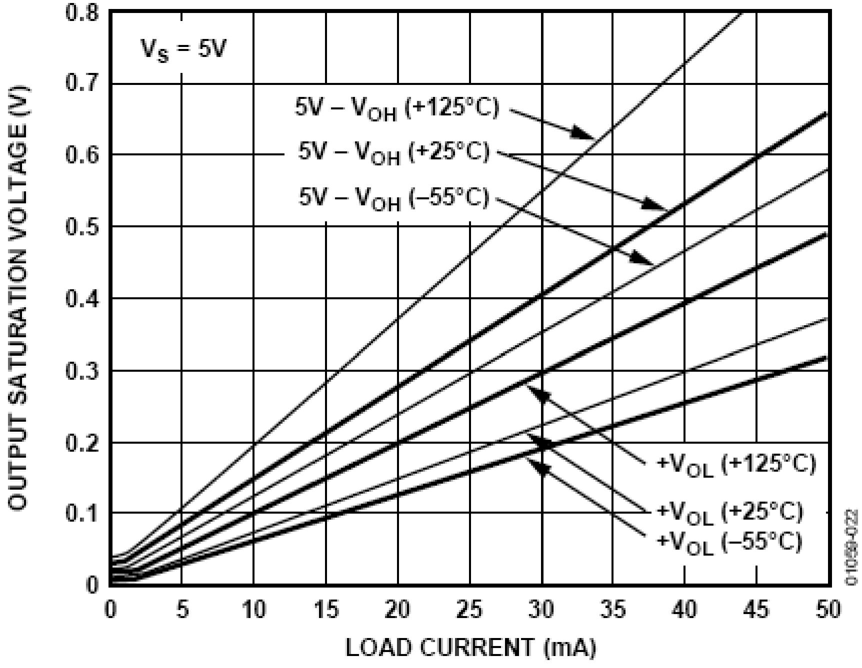
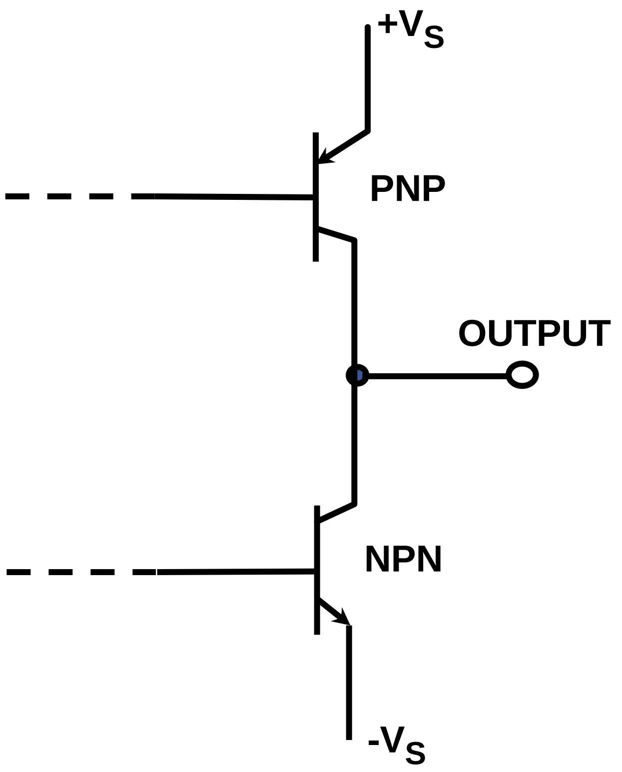
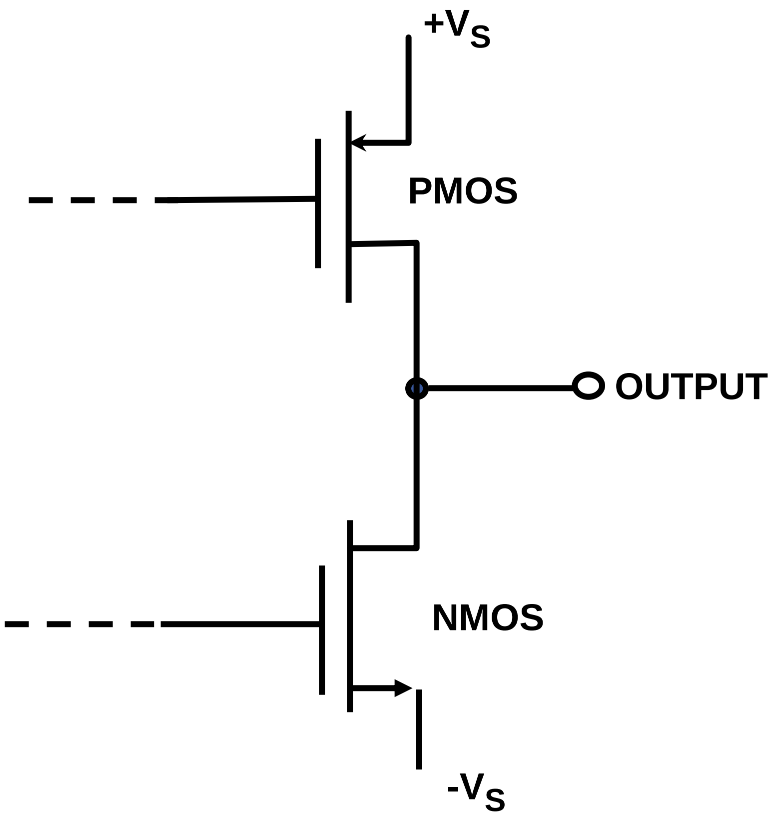


Figure 22. Output Saturation Voltage vs. Load Current

Rail-to-Rail Output Stage



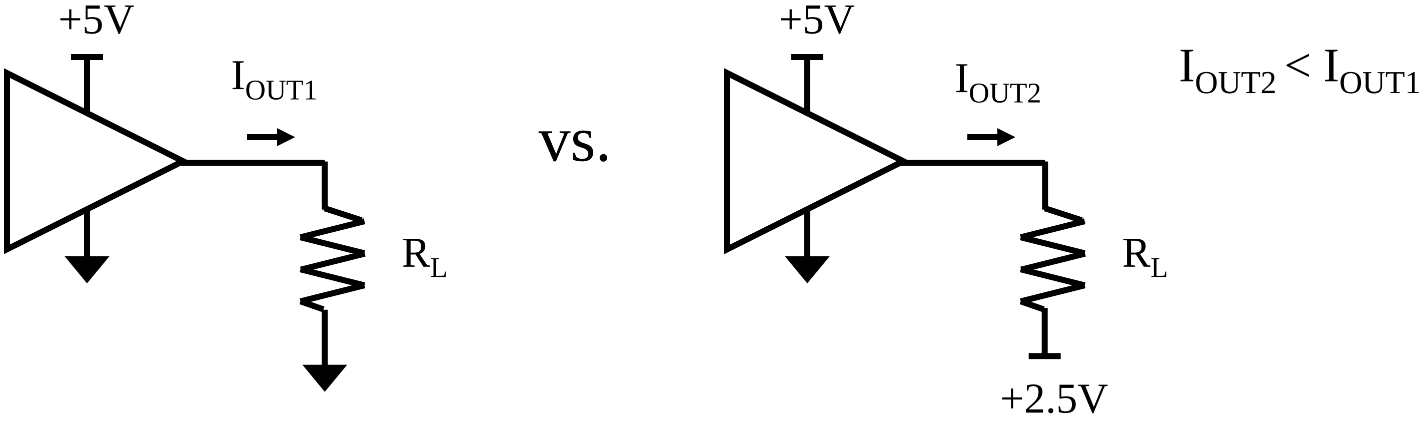


Maximum V_{OUT} limited by saturation voltage

Maximum V_{OUT} limited by FET "on" resistance (10-100Ω)

Load Resistor Connection

- A resistor tied to half-way between the supplies will pull less current
- This increases the maximum output voltage swing
  - Because the output current is lower than if R_L is tied to ground



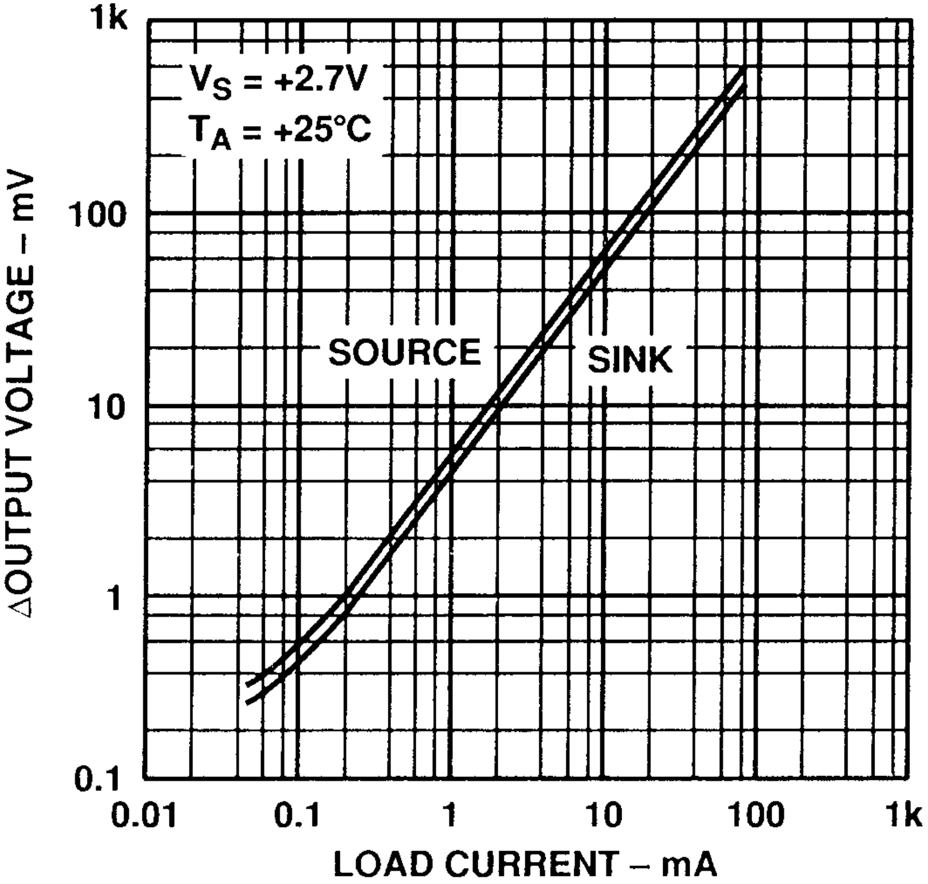
Specifying $V_{OUT,MAX}$

- **There are a number of ways to specify a rail-to-rail output stage in a datasheet**

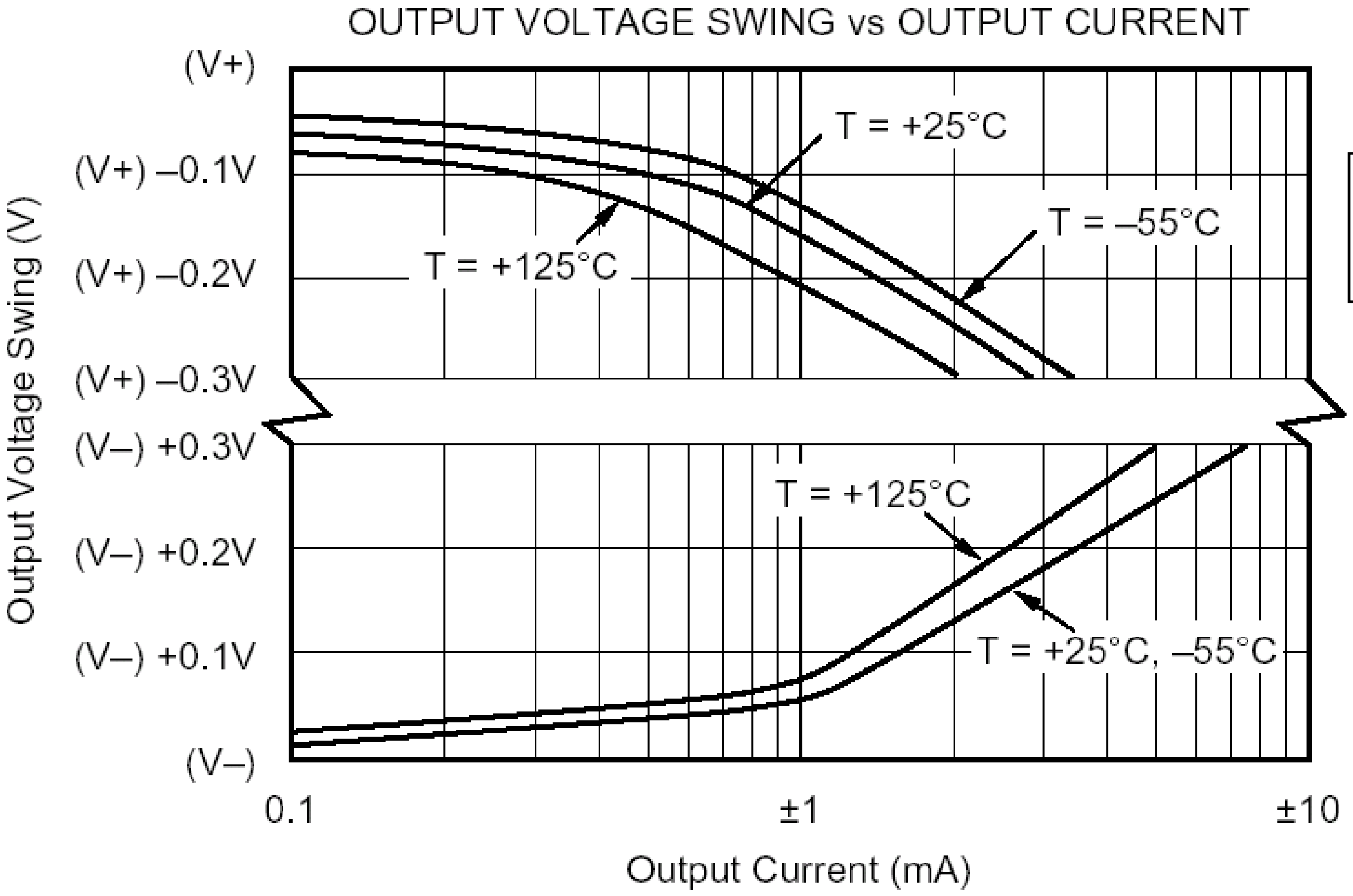
- **Always check for three things:**
  - **What is the supply voltage?**
  - **What is the output current at the V_{OUT} specified?**
  - **Where is the load resistor tied?**
    - Ground, V+, ACOM?

Look at a V_{OUT} vs. I_{OUT} Graph

It is the easiest to understand, regardless of where R_L is tied.

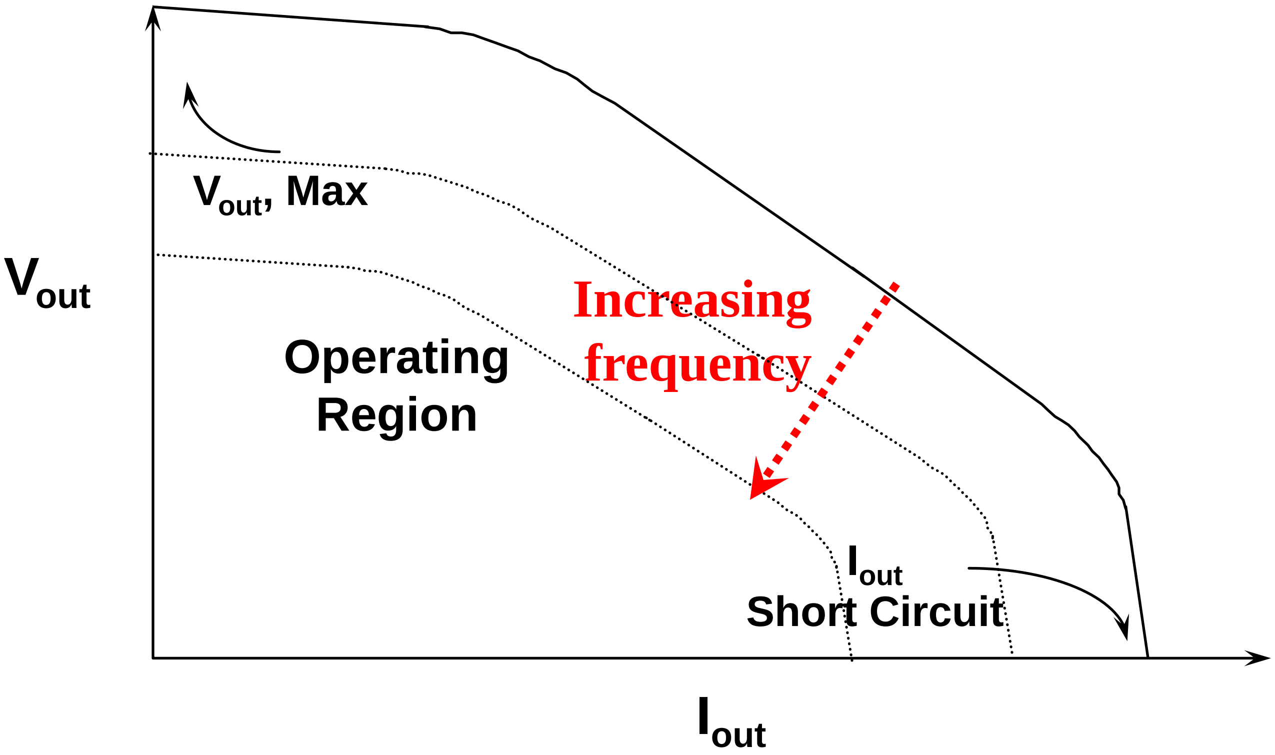


Not as Good as Previous R-R Output



150mV dropout at 1mA sourcing

V_{OUT} vs. I_{OUT} Can Change With Frequency



- $V_{OUT,MAX}$ & $I_{OUT,MAX}$ are specified at DC
- Operating Region Decreases with Increased Frequency

Low Power Amplifiers

- The gain-bandwidth product and slew rate are proportional to supply current
  - High speed amplifiers require more supply current
- For general purpose amplifiers (<5MHz)
  - An amplifier is considered low power if it draws less than 100μA of supply current
- For high speed amplifiers (>100MHz)
  - Low power is 4mA or less when enabled
  - Power-down can reduce current to 0.3μA max
- With some amplifiers, I_{SY} will vary with:
  - Output voltage
    - Higher (or lower) V_{OUT} pulls more current through the output stage – up to 4x!
  - Input common mode voltage
    - A result of unbalanced rail-to-rail input stages

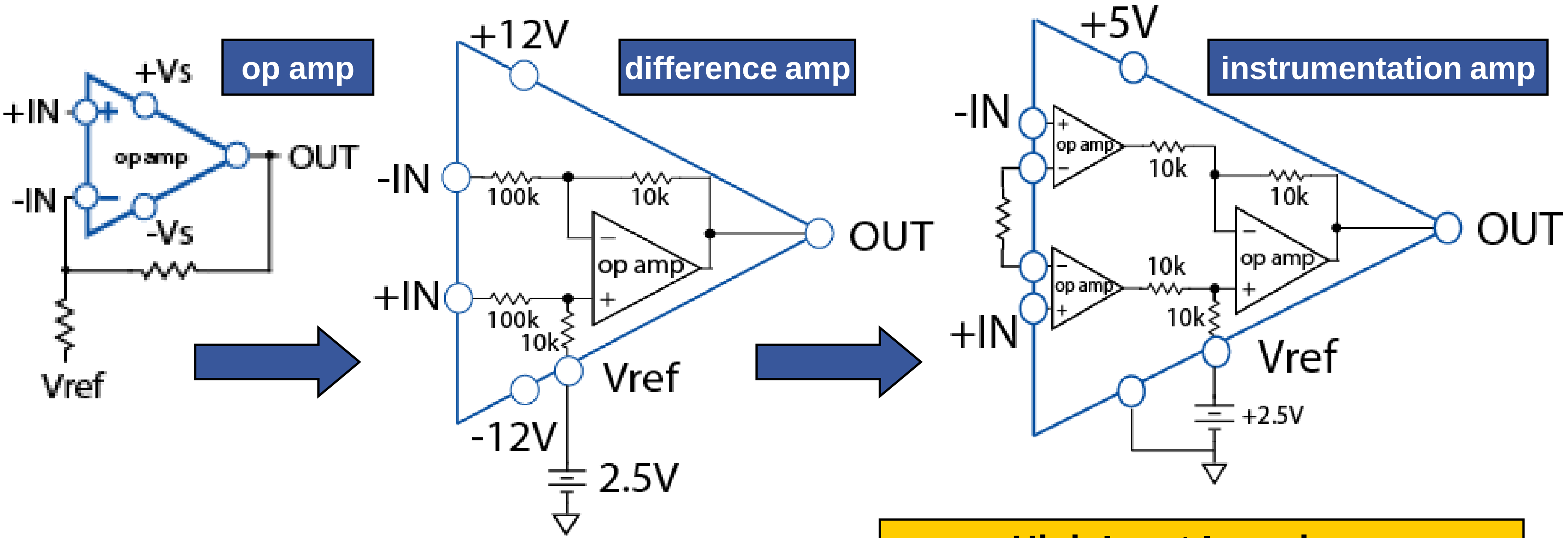
Low Voltage Op Amps

- **Many competitors claim their amplifiers work at low voltages**
- **What is meant by "low voltage"?**
- **Anything +3.0V or lower, and dropping…**
  - **Soon it will < +2.7V**
- **What is meant by "works"?**
  - **Observe the VDD range in the conditions for the PSRR spec**
    - Low VDD voltages may increase the input offset voltage, which is important for low-offset voltage applications
  - **Observe the maximum output voltage and output current specs at the lower supply voltage**
    - Make sure they are suitable for your application

Other types of Amplifiers

- Difference Amps
- Instrumentation Amps
- Log Amps
- Variable Gain Amps
- Differential Amplifiers

Amplifier Integration



Resistor Divider Input Conditions Input Voltages Larger than Supply Rails Vin = 120V. +/-Vs = 12V

Matched Resistors 0.01%

High CMRR vs. Freq, Temp

Level Shift, diff to single ended

Single IC Solution

High Input Impedance

Matched Resistors 0.01%

High CMRR vs. Freq, Temp

Level Shift, Diff to single-ended

Single resistor set the gain

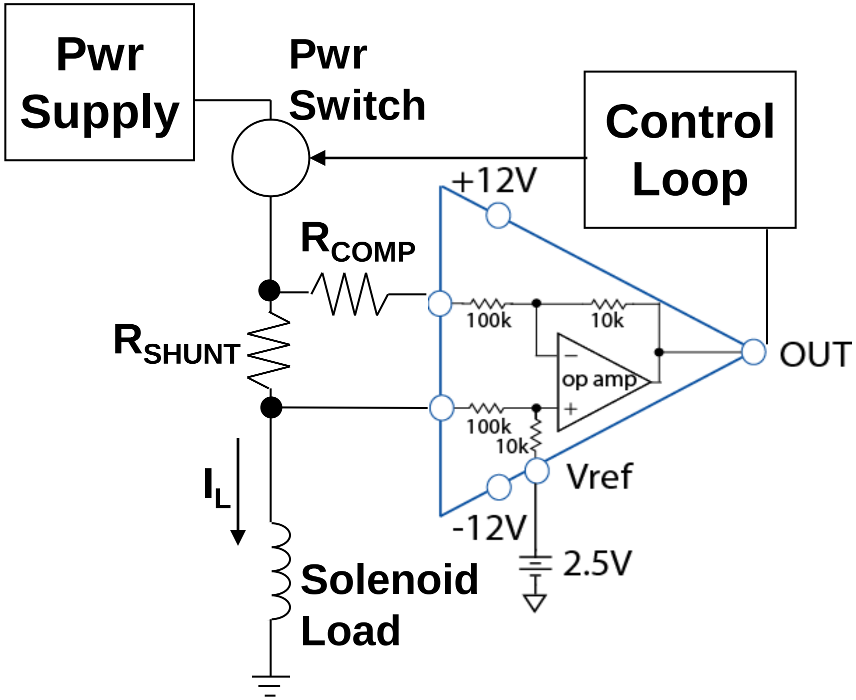
"A device that measures small, precision signals in a noisy environment"

Difference Amplifier Application

High Side Current Sensing

- **Applications:**
  - Linear Solenoid Control (Hydraulics)
  - Motor Control
  - PLC Front-End
- **Product Selection**
  - Low $R_{SHUNT} \therefore$ low V_{os} important
  - Tolerate & reject high CMV
  - Temperature Drift
  - Common Mode Voltage Range:

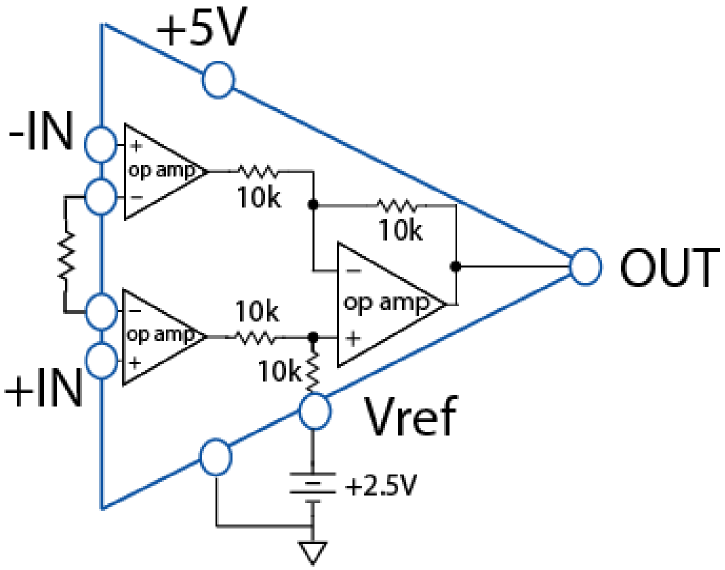
-5 to +68V	±120V	±270V
AD8205 G = 50 Lowest Cost	**AD628** Programmable Gain	**AD629** G = 1

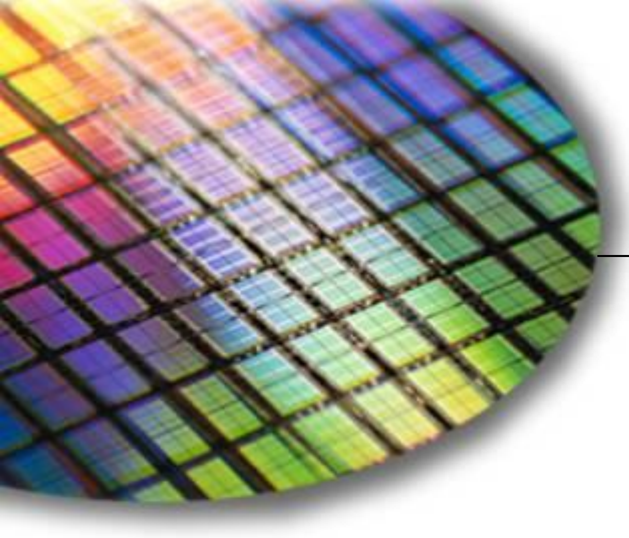


Instrumentation Amps

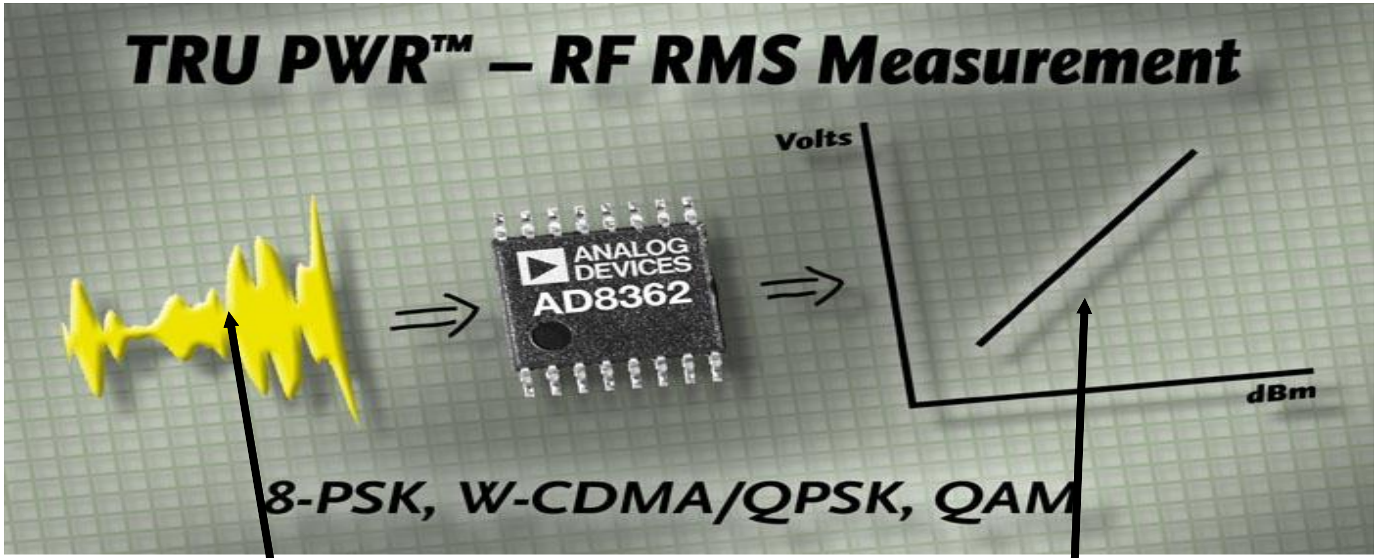
Amplification & CMR

- **Advantages**
  - **Balanced, high impedance load**
  - **High CMR @ power line freq**
    - Rejects common mode noise when a sensor is located remotely from amp.
  - **Vref enables bipolar output with single supply operation**
- **Types of In Amps**
  - **Lowest drift : Chopper Stabilized In-Amps**
  - **Most flexible: Programmable Gain & Offset**





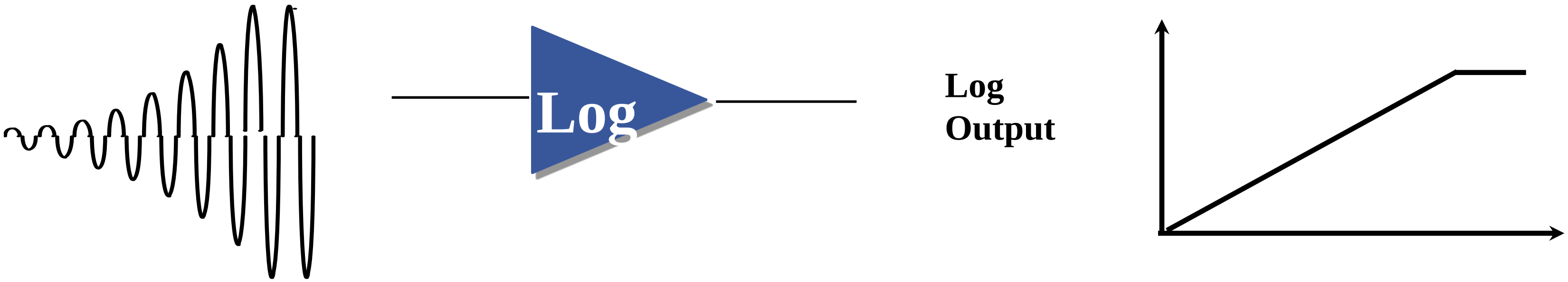
Log Amplifiers and RMS Power Detectors



Flat output despite Varying Crest Factor (Peak to Average Ratio)

What Does a Log Amp Do?

High Dynamic Range Signal Measurement



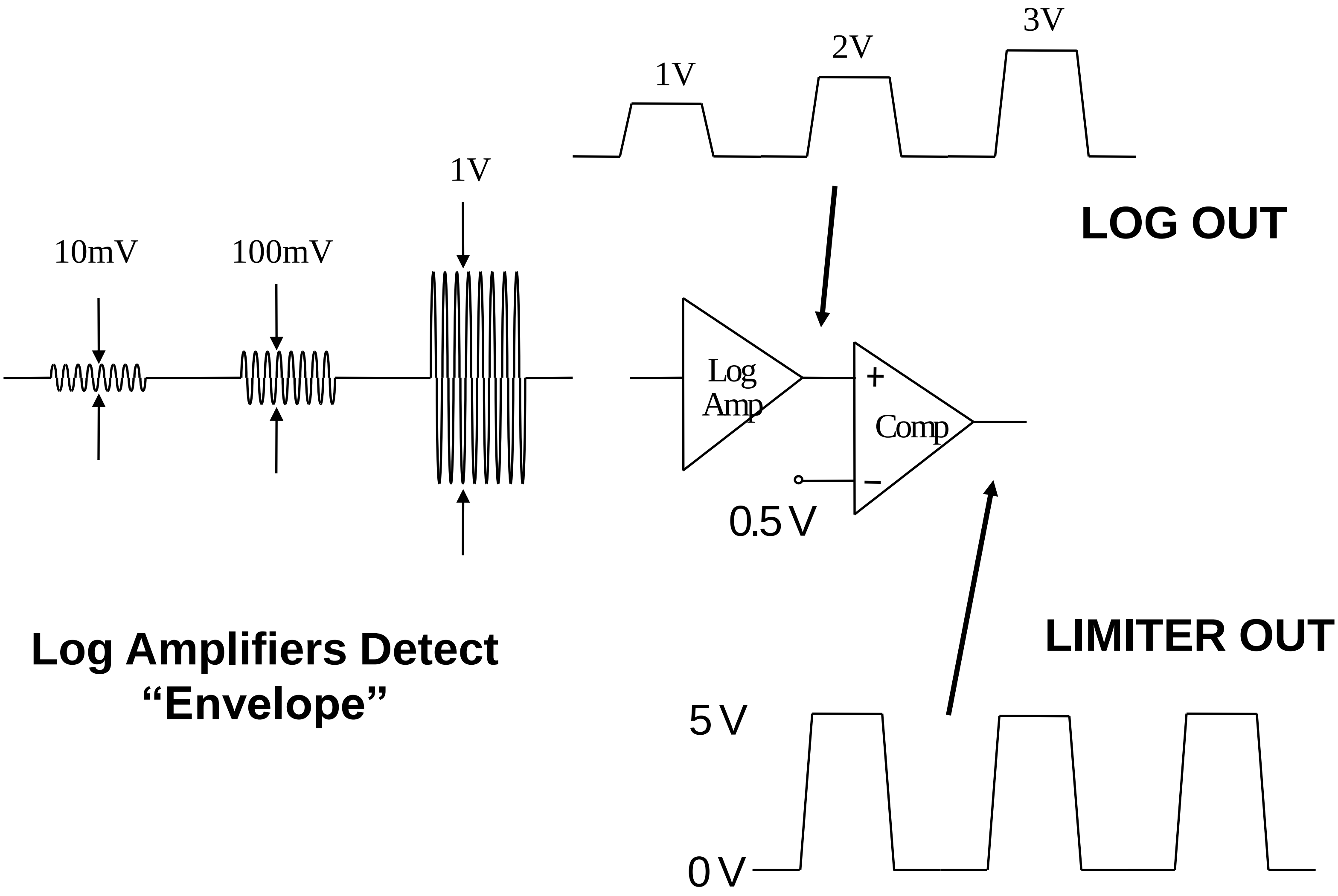
output signal

Large Dynamic Range RF Signal - Handles nanovolt to volt signal levels!

What is it used for?

- **To measure/control power in a radio transmitter**
- **To measure received signal strength (RSSI) in radio receivers**

What does a Log Amp Output show?

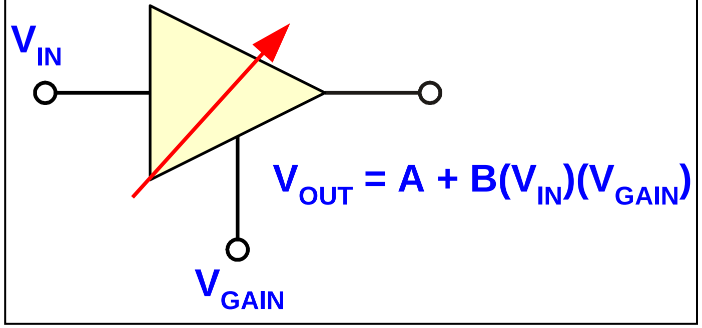


Log Amplifiers Detect "Envelope"

Variable Gain Amplifier (VGA)

- An amplifier whose gain can be electronically controlled. It is symbolized as an amplifier with an electronic volume control pin V_{GAIN}
- Amplifiers used when the gain of the circuit must change quickly.
  - A separate voltage sets the gain of the amplifier
- Used for:
  - Time Gain Amplification (TGA) as in Ultra sound:
    - Ultrasound and Sonar Imaging
  - High Performance Automatic Gain Control (AGC) Systems

VGA - SYMBOLICALLY

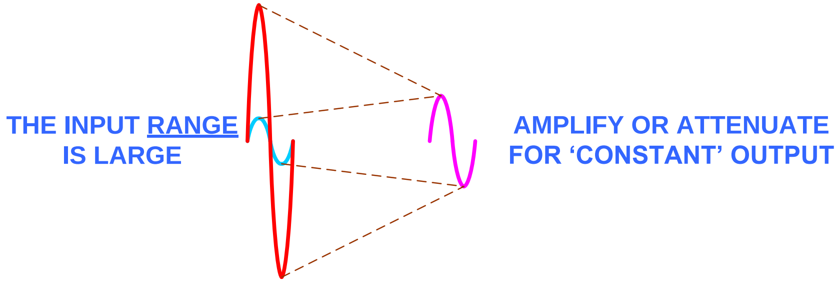


$V_{OUT} = A + B(V_{IN})(V_{GAIN})$

Two Types of VGA Applications

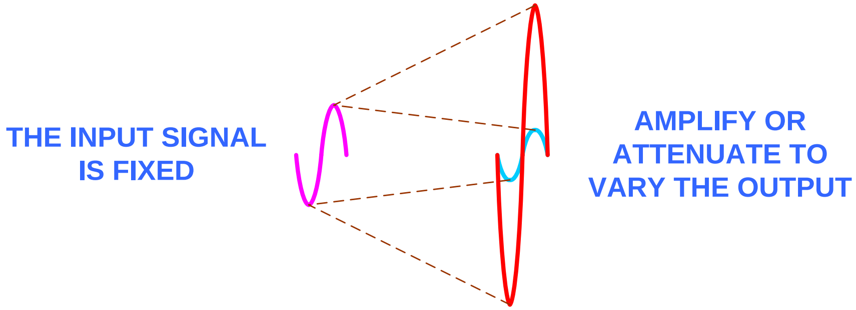
Maintain a Constant output:

As the Input signal level varies, the output level is maintained relatively constant. Example: AGC circuit in a receiver, ultrasound, etc.



The Input Signal Remains Constant:

The input signal level is constant, and it is desired to vary the output. Example: Output level control in a transmitter.



Why are VGAs Used?

- **The Function of a VGA is to Extend the Dynamic Range of the System in Which it is Used**

- **Example:**
  - **The dynamic range of a 10-bit converter is 60 dB**
  - **With a 60dB VGA, the total range is extended to 120dB**
    - Approximately equivalent to a 20-bit ADC
  - **This dynamic range is impossible to achieve with a stand-alone ADC at high sampling rates**

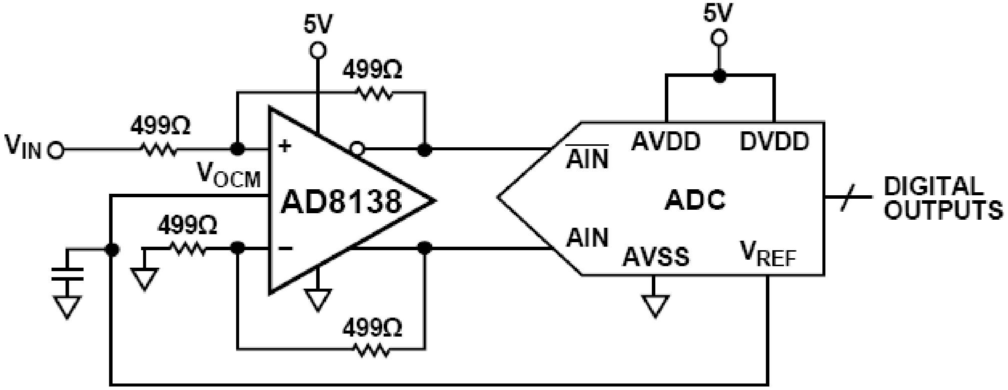
- **Key Attributes:**
  - **Linear-in-dB and/or Linear-in-Gain Control Inputs**
  - **Some Include an Integrated Low Noise Amplifier (LNA)**
  - **Low Noise in the Signal Path**
  - **Single Ended or Fully Differential Signal Chain**
  - **Low Power**
  - **Singles, Dual and Quad Channel Versions Available**

Differential Amplifiers

Performance Advantages

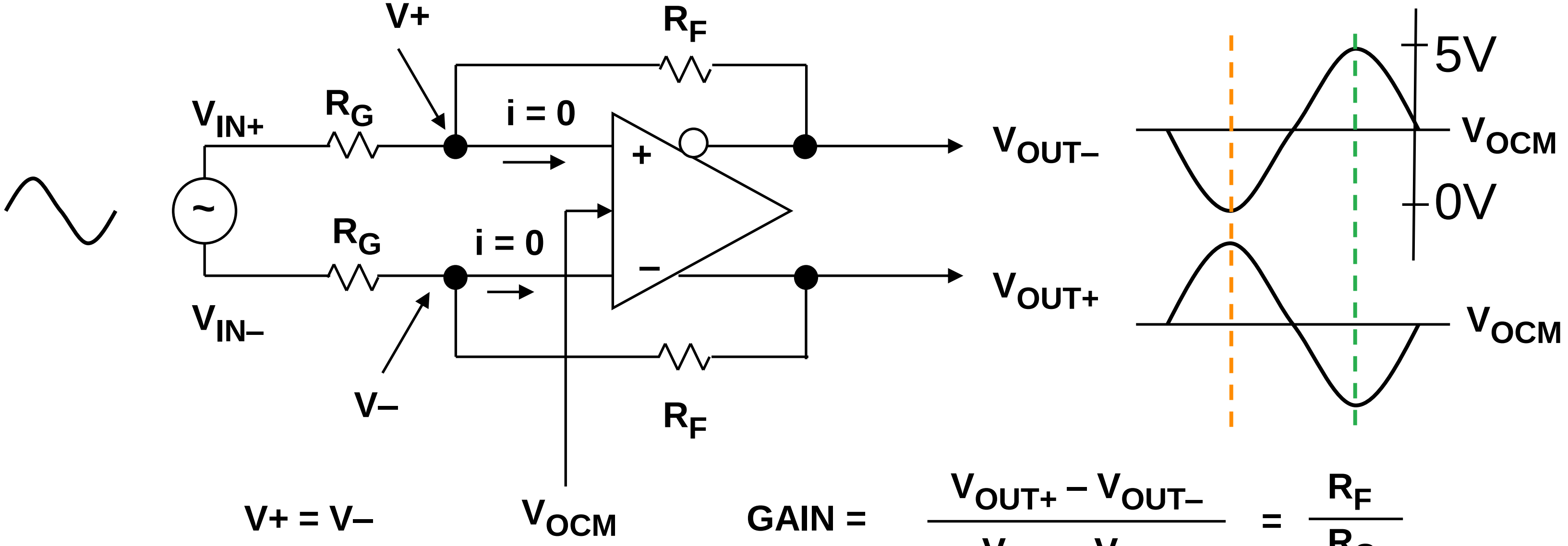
- Rejects ground-based noise – important in single supply systems
- High common-mode noise rejection
- Flexible input common-mode voltage levels

TYPICAL APPLICATION CIRCUIT



- Twice the input signal swing in low voltage, single-supply applications
- Reduced second-order distortion products
- Differential input ADCs require a high performance differential driver

Analyzing Voltage Levels in Differential Amplifiers



$V+ = V–$

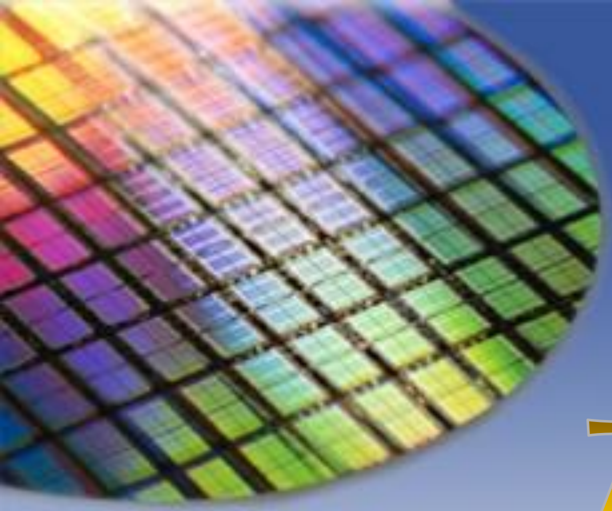
$$\text{GAIN} = \frac{V_{OUT+} - V_{OUT-}}{V_{IN+} - V_{IN-}} = \frac{R_F}{R_G}$$

- + and – input currents are zero
- + and – input voltages are equal
- Output voltages are 180° out of phase and symmetrical about V_{OCM}
- Gain = R_F/R_G

- $V_{OUT+} - V_{OUT-}$ = 5V – 0V = 5V
- $V_{OUT+} - V_{OUT-}$ = 0V – 5V = -5V
- $V_{OUT} = \pm 5V$ … 10V swing

Summary

- **Many specifications will affect how you choose an op amp**
  - DC performance
  - AC performance
- **Specialty amplifiers offer improved performance and integration for some applications**
  - Difference Amps
  - Instrumentation Amps
  - Log Amps
  - Variable Gain Amps
  - Differential Amps



谢谢！

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